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Radian Corp, Austin, TX

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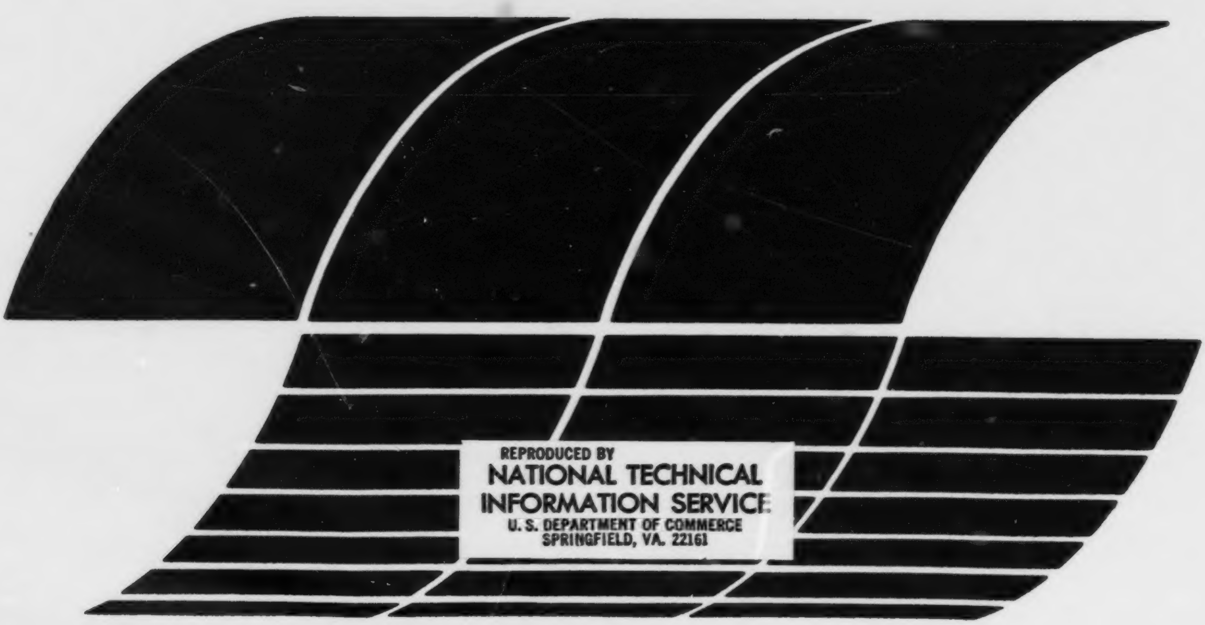
Comparison of the Availability and Reliability of Equipment in the Electric Utility Industry

Interagency Energy/Environment R&D Program Report



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ABSTRACT

This report presents the findings of a study to compare the reliability/availability of flue gas desulfurization systems with equipment commonly used in the electric utility industry. Because many of the parameters used to report performance data for these systems have different definitions from one data reporting system to another, a direct comparison cannot be made. For this reason, a comparison model was developed to incorporate such factors as reliability, development status, and repair effort to result in a single statistic which can be used to directly compare dissimilar pieces of equipment or systems.

Results of this study indicate that a statistically meaningful comparison of the reliability/availability of utility and FGD systems cannot now be made, primarily because of the small amount of FGD system performance data currently available. A meaningful comparison can be made only after more FGD systems are installed and more complete performance records become available.

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CONVERSION TABLE

It is EPA policy to report measurements in the international system of metric units. For clarity of presentation, units used in this report are those commonly used in engineering calculations in the U.S. Factors to convert the units used in this report to metric units are provided below.

To convert from	To	Multiply by
Btu	Joules	1055.1
Btu/lb	Joules/gram	2.32
Cubic feet	Cubic meters	0.028
Standard cubic feet	Normal cubic meters	0.0268
Acres	Square meters	4046.8
Gallons	Liters	3.785
Inches of H_2O	Kilograms/square meters	25.4
Pounds	Kilograms	0.454
Tons	Kilograms	907.18
°F	°C	(°F-32) x 0.555

SECTION 1

EXECUTIVE SUMMARY

A controversy concerning the reliability/availability of flue gas desulfurization (FGD) systems has continued for several years between members of the electric utility industry and the Environmental Protection Agency (EPA). The electric utility industry maintains that FGD technology is unreliable while the EPA maintains it is reliable. Radian Corporation has been contracted by both the Environmental Protection Agency and the Council on Environmental Quality to compare the commercial and technical status and feasibility of the FGD systems with respect to conventional equipment presently accepted and used by the electric utility industry.

Many parameters are currently being used to report the performance of electric utility components and FGD systems. These parameters may have the same name but different definitions from one data reporting system to another. Additionally, there is no one parameter within the existing data bank that can be used directly for comparison and ranking of dissimilar pieces of equipment or systems. In an attempt to directly compare the relative merits of FGD systems and utility equipment components, a Figure of Merit was developed. The Figure of Merit is a parameter which incorporates such factors as reliability, development status, and repair effort; and results in a single statistic which can be used to compare dissimilar pieces of equipment or systems.

There are four major utility equipment items which are of interest to this study: boilers, turbines, generators, and gas turbines. These items are currently used by virtually every utility in the United States. Gas turbines are the least common of these equipment items, although there are more than five hundred gas turbines currently in operation. There are two basic reasons for selecting these utility components for study. First, each is generally accepted by the electric power utility industry as being commercially demonstrated technology. Second, data has been recorded and in many cases is available concerning the reliability, availability, and failure rates of each of these equipment items.

The evaluation of performance data for FGD systems was limited exclusively to lime and limestone systems for the following reasons: 1) lime/limestone FGD systems have been installed and operated on a commercial scale in the United States; 2) three full scale (65 MW or larger) lime/limestone FGD systems have a relatively long (greater than 3 years) operating history; 3) lime/limestone FGD systems are considered commercial technology by the EPA; and 4) performance data for six lime/limestone FGD systems are readily available. An evaluation of the literature indentified 17 operating lime/limestone slurry scrubbing processes. However, 5 of the 17 lime/limestone systems are treating flue gas from units under 50 MW in size. In addition, long-term (greater than 1 year) performance data does not exist for 6 of the 12 systems treating flue gas from units larger than 50 MW. As a result of this screening process, the following 6 FGD systems were identified as best suited for detailed study.

1) Arizona Public Service Company's Cholla Generating Station - Unit No. 1

2) Commonwealth Edison Company's Will County Station - Unit No. 1

3) Duquesne Light Company's Phillips Station

4) Kansas City Power and Light Company's LaCygne Station

5) Kentucky Utilities Company's Green River Station

6) Louisville Gas and Electric Company's Paddy's Run Station - Unit No. 6

Three major conclusions can be drawn from the results of this study. First, a statistically meaningful comparison of the reliability/availability of utility and FGD systems cannot now be made, primarily because of the small amount of FGD system performance data currently available. A meaningful comparison can be made only after more FGD systems are installed and more complete performance records become available. Second, the comparison model or Figure of Merit provides a better basis of comparing or ranking dissimilar pieces of equipment or systems than any single parameter currently being recorded. At this time, only Term I and Term II of the Figure of Merit can be used. The learning curve portion, Term III of the Figure of Merit, does not have sufficient available data. Finally the products of Term I and Term II of the Figure of Merit are greater than 50 for an equipment installed by the Electric Utility Industry. FGD Systems must, therefore, establish an operating history, such that the same product within the Figure of Merit is greater than 50 in order to demonstrate performances comparable to utility components.

This report combines the FGD operating history reported by Radian in EPA Contract #68-02-1319, Task 62 with an entirely new utility data search. Thus Section 5.0 and parts of Sections 7.0 and 8.0 pertaining to the utility data have been completely rewritten. The report has been completely reissued to preserve the context of the material and to retain all of the material within one report.

SECTION 2

INTRODUCTION

The controversy surrounding the implementation of flue gas desulfurization technology in the electric utility industry has continued for at least the past five years. While the spokesmen on both sides to some degree have changed, and while the arguments have undergone periodic variations, a consistent theme on the part of the electric utility industry is that scrubbers represent unreliable technology and that technology should not be forced upon the electric utility industry unless it is at least as reliable as technology presently utilized in that industry. This has been the crux of the issue. The Environmental Protection Agency (EPA) maintains the technology is reliable; the electric utility industry steadfastly maintains it is unreliable.

The positions of both EPA and the electric utility industry are contained in a document entitled: Report of the Hearing Panel - National Public Hearings on Power Plant Compliance with Sulfur Oxide Air Pollution Regulations (EN-111). This document summarizes the public hearings which took place during the period October 18, 1973 through November 2, 1973.

The EPA panel which conducted the hearings prepared findings and recommendations based on the testimony presented. Of principal interest is the following:

> "Although most utility witnesses testified that FGD technology was unreliable, that it created difficult sludge disposal problems, and that it cost too much, the hearing panel finds, on the basis of utility and FGD vendor testimony, that the alleged problems can be, and have been, solved at a reasonable cost. The reliability of both throwaway-product and saleable-product

FGD systems has been sufficiently demonstrated on full scale units to warrant widespread commitments to FGD systems for SO_x control at coal- and oil-fired power plants."

This finding from the 1973 hearings has fueled the fires for debate on the issue of reliability of flue gas desulfurization (FGD) systems. Both the Environmental Protection Agency and the Electric Power Research Institute have programs underway to address the issue of FGD system reliability. In general, these studies are reporting improved scrubber reliability and better performance over that experienced in the recent past. The question remains as to whether FGD technology is too unreliable compared to other components in the electric utility industry.

Under contract to both the Environmental Protection Agency and the Council on Environmental Quality, Radian Corporation has conducted a study to compare the reliability of FGD systems with other components in the electric utility power generating system. Data and results drawn from this study are presented in the following sections of this report. Section 3.0 is a general description of the FGD and utility systems compared. Section 4.0 outlines the comparison basis and Sections 5.0 and 6.0 present the utility and FGD data. Study results are given in Section 7.0 and conclusions and recommendations in Section 8.0.

2.1 PROGRAM OBJECTIVE

The overall objective of this study was to compare the reliability/availability of FGD systems with conventional fossil fueled equipment presently accepted and used by the electric utility industry. To accomplish this objective a comparison basis was formulated, and available performance data were gathered on both utility and FGD systems.

2.2 APPROACH

The initial task in this study was to formulate a basis for comparing FGD and utility equipment operating data. Since there is no standard procedure for reporting reliability data, a comparison of utility component and FGD system reliability is nontrivial. The requirement for a standard comparison basis was of prime importance to the conduct of this study. The comparison basis was formulated in an attempt to normalize the differences in data reporting, system design, and operating practices.

Data collection and analysis were identified concurrently with the formulation of the comparison basis. A literature search was conducted to retrieve reliability data on utility system components and FGD systems available in the open literature. In addition, contacts were made with the Federal Energy Administration (FEA), the Edison Electric Institute (EEI), the National Association of Regulatory Utility Commissions (NARUC), the Electric Power Research Institute (EPRI), the American National Standards Institute (ANSI), PEDCO Environmental Specialists, Inc., and several electric utility companies. Attempts were made to gather reliability information from all known and potential sources to obtain complete data for comparison of the various systems. The final task was to organize, analyze, and compare the collected data on utility and FGD systems using the comparison method developed in the first task.

SECTION 3

DESCRIPTIONS OF UTILITY EQUIPMENT AND FGD SYSTEMS

In this section, brief descriptions are presented of the electric utility equipment and the FGD systems that were evaluated during this study. The intent of the utility equipment descriptions is to provide an understanding of the function of each of the equipment items and to illustrate how each item fits into the overall electricity generating system. Since FGD systems are very site-specific and are few in number within the United States, the intent of the FGD system description is to highlight the differences between the various installations. Differences in both process design and process operations are discussed.

3.1 ELECTRIC UTILITY EQUIPMENT DESCRIPTIONS

The four major utility equipment items of interest to this study are boilers, turbines, generators, and gas turbines. These items are currently used by virtually every utility in the United States. Gas turbines are the least common of these equipment items, although there are more than five hundred gas turbines currently in operation.

There are two basic reasons for selecting these equipment items for study. First, each is generally accepted by the electric power utility industry as being commercially demonstrated technology. Second, data has been recorded and in many cases is available concerning the reliability, availability, and failure rates of each of these equipment items.

Nuclear unit operating data is not included in this study because nuclear units represent a portion of the electric utility industry in which FGD systems will never be used. Thus a comparison of nuclear unit with FGD system operating parameters will not clarify any portion of the present program objectives. Additionally, the nuclear unit operating data is significantly affected by regulatory constraints. These constraints can limit the maximum output of a unit and significantly affect the downtime required for inspection. These constraints have no counterpart for non-nuclear units or FGD systems within the electric utility industry.

Modern electric power generating stations are complex units which employ sophisticated mechanical, metallurgical, and electrical technology. Figure 3-1 presents a highly simplified flow scheme which identifies the general equipment categories important in this study. No attempt is made here to distinguish between boiler types, equipment manufacturers, or equipment design or quality. The primary reason for this is because most of the reliability/availability data recorded are also in general categories.

The three major flowpaths shown in Figure 3-1 are water/steam, combustion gas, and electrical. Many design constraints are placed on the equipment which handle each of these flows. The following five sections briefly describe the major equipment items mentioned above. The numbers in Figure 3-1 refer to the major equipment items discussed.

3.1.1 Utility Boilers

The principle of a modern water tube boiler is simple. The boiler consists of steel drums or headers connected by a number of steel tubes, and arranged in a furnace so that the hot gases have to pass through the bank of tubes on their way to the stack. Hot combustion gases flow around the tubes, transferring their heat to the water or steam within the tubes. The steam in turn is collected and may be heated to a temperature well above the

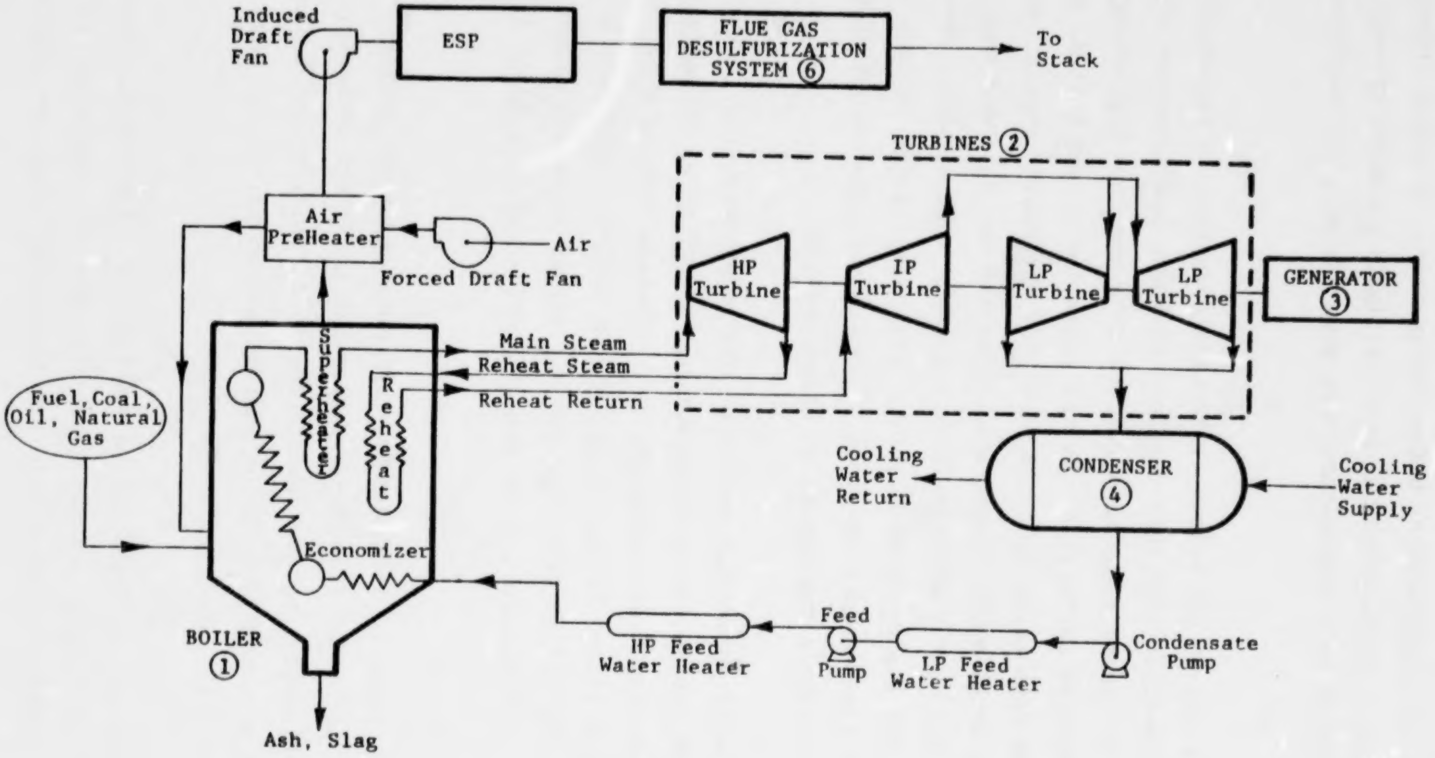
Induced Draft Fan
ESP
FLUE GAS DESULFURIZATION SYSTEM ⑥
To Stack
TURBINES ②
Air PreHeater
Air
Forced Draft Fan
HP Turbine
IP Turbine
LP Turbine
LP Turbine
GENERATOR ③
Superheater
Reheat
Main Steam
Reheat Steam
Reheat Return
Fuel, Coal, Oil, Natural Gas
Cooling Water Return
CONDENSER ④
Cooling Water Supply
Economizer
BOILER ①
Feed Pump
HP Feed Water Heater
LP Feed Water Heater
Condensate Pump
Ash, Slag

Figure 3-1. Simplified flowscheme for an electric power generating station.

saturation temperature (superheated) before being used. In other separate portions of the boiler, steam which has been partially expanded through a turbine may be reheated to a temperature very near the original superheat temperature.

As steam flows out of the boiler it becomes necessary to replenish the water that was evaporated. For this reason feed pumps are necessary to supply water to the boiler. These pumps must operate at a pressure high enough to overcome the pressure in the boiler. In the operation of any boiler, it is essential always to keep water in the boiler. If the boiler should run low on water, the tube metal would become hot, loose its strength and rupture. At the same time, the boiler should not be filled to a point where there is insufficient room for the steam to collect. Typically, level control devices or steam and water flow devices are used to insure that the amount of water entering the boiler equals the amount of steam leaving.

Boiler feed water is usually heated before being delivered to the boiler. A feed water heater (using low pressure exhaust steam) or an economizer or both are used to do this. An economizer is a separate bank of tubes through which the feed water passes before it enters the boiler. This bank of tubes is placed between the boiler tubes and the air heater to absorb some additional heat from the combustion gases thus improving the economy of the boiler.

Air is heated prior to introduction into burners in the boiler. The incoming cold air is heated from the hot flue gas in an air preheater. Preheating the air primarily improves the thermal efficiency of the boiler, but also helps stabilize combustion in the burners and in pulverized coal firing, is used to dry the coal during pulverization.

Air preheaters can be divided into two classes. Tubular air preheaters are of fin tube construction and are generally used in industrial boiler applications and smaller utility boiler applications. The regenerative air preheater is generally in the form of a large wheel made of honeycomb steel. The wheel slowly rotates. One sector of the wheel is exposed to the flue gas and is heated. The heated section of the wheel then leaves the flue gas duct and enters the combustion air duct. In the combustion air duct, the hot honeycomb steel gives up its heat to the air. The wheel continues to rotate and the cycle is repeated. Wheel rotation speeds are usually .05 to 5 rpm. The regenerative air preheater is more expensive and more efficient than the tubular preheater. Thus the regenerative preheater is usually applied to the larger and newer utility boilers.

Boilers used in utility applications can be classified into two categories based on the water/steam flow characteristics. These categories are natural circulation and forced circulation. Natural circulation boilers rely on the difference in density of the water and steam to establish and maintain flow throughout the many portions of the boiler. Forced circulation boilers rely on pumps to establish and maintain flow within the boiler.

Forced circulation boilers can be further classified into three subcategories, *i.e.*, controlled circulation, combined circulation and once through units. A complete discussion of the features of each of these boilers can be found in reference BA-185 and FR-P-287.

Natural circulation boilers comprise the largest number and the greatest ranges of capacities and steam conditions now in use in the utility industry. Natural circulation boilers invariably contain a steam drum. The steam drum has many functions, but primarily serves as a space for the separation of steam and water. The steam leaves the drum and the water is allowed to recirculate within the boiler.

Forced circulation boilers came into being in an effort to improve the efficiency of energy conversion from fuel to steam and then to electricity. Higher steam temperatures and subsequently higher pressures offer the potential of better cycle thermal efficiency. However, as the steam pressure increases the difference between the water density and steam density becomes less, until at 3206 psia, the critical pressure, no difference in density can be found. Thus the natural circulation boiler cannot be used and only forced circulation boilers are feasible. Boilers which operate below 3206 psia outlet steam pressure are called subcritical. Boilers operating above 3206 psia are called supercritical.

Supercritical boilers are of the once through type and thus do not contain steam drums. This boiler can be visualized as one long channel, cold fluid (water) at one end and hot fluid (steam) at the other.

Subcritical boilers constructed in accordance with each category discussed, *i.e.*, natural and forced circulation, controlled, combined, and once through exist in utility service.

3.1.2 Turbines

Turbines provide a means for converting energy in the steam into useful shaft work. Simply stated, a turbine is a shaft mounted on two or more sets of bearings. Attached to the shaft are a set of wheels or stages which have blades attached to the rim. These blades, or buckets as they are commonly called, are shaped such that the passage of steam forces the wheel to turn thus turning the shaft. Stationary nozzles set between the rotating stages direct the steam so that it continually drives the buckets.

Turbines are designed to turn at a fixed speed and are equipped with automatic controls to accomplish this. The rotating turbine shaft is coupled to an electric generator rotor which is the means for converting shaft work into electricity.

Turbines can be classified in terms of the steam flow within the case. In simplex turbines, the steam flows in one direction within the case, *i.e.*, from one end to the other. In compound turbines, the steam flows in two or more directions within the case, *i.e.*, steam is admitted at some intermediate point along the length of the turbine, flows to one end, exits and is readmitted to the turbine and flows in the other direction along the axis of the turbine. Thus two simplex turbines are housed in one case.

As turbines become larger, more cases and rotors are required. The cases and rotors can be arranged in series, in parallel or series-parallel. If all rotors are connected and operate from a common shaft center line, the unit is called tandem. If the rotor shafts are parallel, the unit is called crossed. The most common turbine classifications in utility use are tandem-compound and cross-compound. The two or more shafts of a cross-compound unit may operate at the same or different rotational speeds, *i.e.*, 3600/3600 or 3600/1800.

3.1.3 Generators

A generator consists of wire coils turning through the lines of flux from a magnet. As the wire coil interrupts the magnetic flux lines a voltage is produced in the wire, thus generating electricity. A central station generator consists principally of a magnetic circuit, dc field winding, ac armature, and mechanical structure including cooling and lubricating systems. The steam turbine, coupled to the generator rotor, provides the shaft power necessary to turn either the coil through the magnetic flux or to turn the magnet within the coil.

Only one generator is normally coupled to a tandem turbine. Either one or two generators may be coupled to a crossed turbine. Where two generators are used, the generator is called a two-shaft generator. Two shaft generators may in reality be two separate and distinct pieces of equipment but are lumped together in common terminology within the utility industry.

3.1.4 Condensers

The steam exiting the turbine is condensed to create a vacuum at the turbine exhaust. The efficiency of the turbine is improved by allowing it to exhaust into a vacuum rather than to the atmosphere. The condensing steam can easily be returned to the boiler as feed water.

The condenser uses cooling water passing through a bank of tubes to cool and condense the turbine exhaust steam. The steam condensate collects in a "hot well" which serves as a reservoir for a pump returning condensate to the boiler feed water heaters and boiler feed pump.

3.1.5 Gas Turbines

Gas turbines provide a means for obtaining shaft work directly from combustion gases without the intermediate step of steam generation. Figure 3-2 illustrates a simple gas turbine cycle. The compressed, hot combustion gases are used to drive the turbine rather than steam.

A gas turbine can be incorporated into a steam power plant in many ways. These combined cycles are designed to suit each power plant's needs. The turbine exhaust can be used as part of a boiler's combustion air or as a source of boiler feed water preheat. More complex cycles can also be constructed. In many cases, gas turbines are operated to handle peak load conditions.

3.2 FGD SYSTEMS

A significant portion of this study was devoted to ascertaining the availability/reliability of operating lime/limestone flue gas desulfurization systems. This investigation was limited exclusively to lime and limestone systems for the following reasons: 1) lime/limestone FGD systems have been

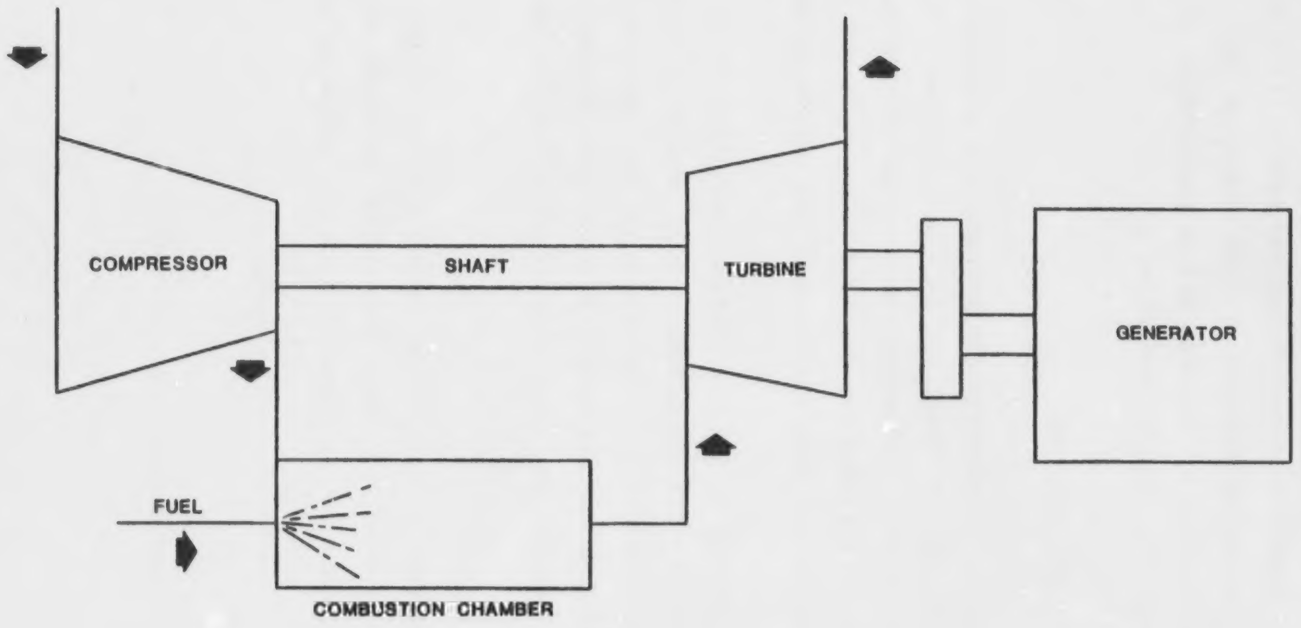
COMPRESSOR
SHAFT
TURBINE
GENERATOR
FUEL
COMBUSTION CHAMBER

Figure 3-2. Simplex-cycle gas turbine flowscheme.

installed and operated on a commercial scale in the United States; 2) three full scale (65 MW or larger) lime/limestone FGD systems have a relatively long (greater than 3 years) operating history; 3) lime/limestone FGD systems are considered commerical technology by the EPA; and 4) performance data for six lime/limestone FGD systems are readily available.

3.2.1 General Lime/Limestone FGD Systems

The lime/limestone flue gas desulfurization process uses a slurry of calcium oxide or calcium carbonate to absorb SO_2 in a wet scrubber. This process is commonly referred to as a "throwaway" process because the calcium sulfite and sulfate formed in the system are disposed of as waste solids. Figure 3-3 illustrates a generalized lime/limestone slurry scrubbing system.

The gas flows from the boiler to the FGD system. Particulates in the flue gas stream can be removed by the SO_2 scrubber or by auxiliary equipment (*e.g.*, an electrostatic precipitator) which processes the gas upstream of the FGD system. FGD systems which do not have auxiliary particulate control often employ a prescrubber designed to remove particulates from the gas just upstream of the absorber.

The actual SO_2 absorber design varies from one application to the next. These designs differ in SO_2 removal efficiency as well as operating reliability. The SO_2 absorber designs can be classified in the following categories:

1) Venturi Scrubber
2) Spray Tower Scrubber (horizontal and vertical)
3) Grid Tower Scrubber
4) Mobile Bed Absorber

Flue gas enters the absorber and is contacted with a lime or limestone slurry. This contact results in the absorption of SO_2 from the gas phase into the liquid phase where the following chemical reactions occur.

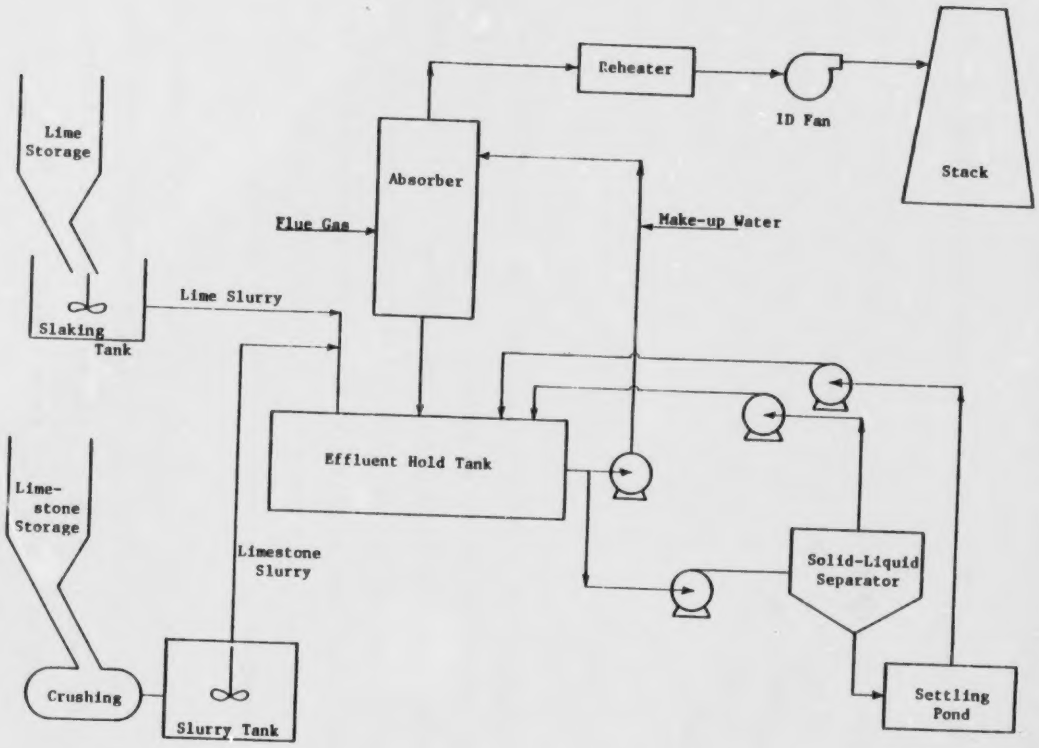
Lime Storage
Slaking Tank
Lime Slurry
Lime-stone Storage
Crushing
Slurry Tank
Limestone Slurry
Flue Gas
Absorber
Reheater
ID Fan
Stack
Make-up Water
Effluent Hold Tank
Solid-Liquid Separator
Settling Pond

Figure 3-3. General lime/limestone FGD system.

For Lime Systems:

$$SO_2(g) + CaO(s) + \tfrac{1}{2}\ H_2O \rightarrow CaSO_3 \cdot \tfrac{1}{2}\ H_2O(s) \qquad (3\text{-}1)$$

For Limestone Systems:

$$SO_2(g) + CaCO_3(s) + \tfrac{1}{2}H_2O \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O(s) + CO_2(g) \qquad (3\text{-}2)$$

In both cases the major reaction product is calcium sulfite ($CaSO_3$).

In addition to SO_2, some oxygen (O_2) is also absorbed from the flue gas. This results in the oxidation of SO_2 and formation of calcium sulfate ($CaSO_4$) (Equation 3-3). The formation of calcium sulfate can result in sulfate scaling which is a problem that has plagued many of the operating lime/limestone FGD systems.

$$\overset{++}{Ca}(aq) + \overset{--}{SO_3}(aq) + \tfrac{1}{2}O_2(g) + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O(s) \qquad (3\text{-}3)$$

The degree of oxidation of sulfite to sulfate can vary considerably, normally ranging from near zero up to 40 percent in utility boiler applications. In some systems treating dilute SO_2 gas streams, sulfite oxidation has reached 90 percent. The acutal mechanism for sulfite oxidation is not completely understood. The rate appears to be a strong function of oxygen concentration in the flue gas and liquor pH. It may also be increased by trace quantities of catalyst in fly ash entering the system.

The feed material for a lime scrubbing process is usually produced by calcining limestone. Feed for a limestone process generally comes directly from the quarry, and is then reduced in size by crushing and grinding. The lime or limestone is mixed with water to form a slurry which is used to absorb SO_2.

Flue gas which exits the SO_2 absorber enters a mist eliminator where droplets of slurry entrained in the flue gas are removed. The flue gas is then reheated and exhausted to the atmosphere through the stack.

The lime/limestone slurry exiting the absorber contains both calcium sulfite and calcium sulfate. This spent slurry is routed to the effluent hold tank which is the point of addition for the lime/limestone feed slurry (Figure 3-3).

The hold tank is essentially a reaction vessel for the precipitation of calcium sulfite and calcium sulfate solids. The tank is designed to allow adequate residence time for the precipitation reactions to occur. Too short a residence time in the hold tank can result in scaling of the absorber.

A continuous stream of 10 to 15 percent solids is recycled to the absorber from the effluent hold tank. In addition, a purge stream is continuously withdrawn from the hold tank for treatment and disposal. This serves to remove calcium sulfite/sulfate solids from the system.

In some applications with an on site disposal pond, solids may be pumped directly from the effluent hold tank to the pond. In closed loop operation, overflow liquor from the pond would then be returned to the FGD system for reuse.

Some installations employ dewatering equipment to minimize the pond area required for sludge disposal. Depending on the physical properties of the solids produced in the FGD system, a thickening device such as a clarifier can be used to increase the solids content to a maximum of about 40 weight percent. Additional dewatering to 60 to 70 percent solids can sometimes be achieved by vaccum filtration. Forced oxidation techniques can be used to produce a sludge with up to 80 percent solids.

Sludge disposal is an integral part of lime/limestone FGD systems. The quantity of sludge produced is large in both weight and volume, and requires a large waste pond or landfill area for disposal. On site sludge disposal is usually performed by sending the waste solids to a large pond. Settling of the solids occurs and pond water is recycled back to the process hold tank for reuse. "Stabilization" methods are currently under development to convert the sludge to structurally-stable, leach-resistant, landfill material. These methods could be used when on site disposal is not possible. The stabilized material can then be trucked to an off site area for landfill.

3.2.2 Specific Lime/Limestone Systems

An initial screening of PEDCo's Bi-Monthly Status Report-Flue Gas Desulfurization Systems identified 30 operational FGD systems. Of these 30 systems 17 are lime or limestone slurry scrubbing processes. However, 5 of the 17 lime/limestone systems are treating flue gas from units under 50 MW in size. In addition, long-term (greater than 1 year) performance data does not exist for 6 of the 12 systems treating flue gas from units larger than 50 MW. As a result of this screening process, the following 6 FGD systems were identified as best suited for detailed study.

1) Arizona Public Service Company's Cholla Generating Station - Unit No. 1

2) Commonwealth Edison Company's Will County Station - Unit No. 1

3) Duquesne Light Company's Phillips Station

4) Kansas City Power and Light Company's LaCygne Station

5) Kentucky Utilities Company's Green River Station

6) Louisville Gas and Electric Company's Paddy's Run Station - Unit No. 6

A brief description of each of these 6 systems appears in Appendix D.

SECTION 4

COMPARISON BASIS

Many parameters are currently being used to report the performance of electric utility equipment and FGD systems. These parameters may have the same name but different definitions from one data reporting system to another. Additionally, there is no one parameter within the existing data bank that can be used directly for comparison and ranking of dissimilar pieces of equipment or systems.

In an attempt to directly compare the relative performance of FGD systems and utility equipment components a Figure of Merit was developed. This parameter incorporates such factors as reliability, development status, and repair effort; and results in a single statistic which can be used to compare different processes. The following sections describe the development and use of the Figure of Merit.

4.1 DEVELOPMENT OF THE COMPARISON BASIS

The need for a method of comparison which would permit the relative performance of utility equipment and FGD systems to be compared on an equivalent basis became evident early in the conduct of this study. In developing a comparison basis or Figure of Merit, the following goals were established.

1) Existing data should be applicable to the comparison technique.

2) New data, if required, should not be too difficult to obtain.

3) The comparison technique should be relatively simple to compute and apply.

4) The comparison technique should include at least:

    a) A measure of availability
    b) A measure of maintenance/economic requirements
    c) Scale-up or learning function

These goals then define the type of comparison to be formulated. In addition, these goals define a tool which has present usefulness rather than theory which may never have sufficient data for application, except possibly for historical value.

Existing data should be used where available and applicable. This premise was established such that a whole new data base was not required. The primary thrust of the comparison technique is to illuminate present discussions with existing data. A comparison technique which must wait months or years for the start of data acquisition, and then longer before meaningful interpretations could be obtained, was to be avoided if at all possible.

Any new data which is required to complete the comparison must be obtainable without creating additional difficulties for the reporting or collecting agencies. New data requirements could come from two possible directions. The equipment operating logs may contain some of the needed information. Data not now recorded may have to be added to the data requirement list of selected installations. In either case, the collection and reporting of new data requirements will be minimized and will not require the addition of sensing or logging equipment.

The comparison technique must be relatively simple to compute and apply. Preferably no more than a desk calculator will be required for computational purposes. The comparison need not have physical meaning, such as service hours, etc., but must at least represent a coefficient of performance and must display a spread or ranking within which each component or system can be easily evaluated or ranked.

The preceding discussion describes the functional requirements of the comparison technique. There are three specific requirements which must be added to the functional requirements; namely, a measure of "availability," a measure of the maintenance/repair effort required to achieve a given equipment performance, and a learning function.

Historically, "availability" is a term which has been used to describe the percentage of time a piece of equipment is ready to perform a specific task. Several different types of availability are currently being used and erroneously being compared one to another within the electric utility industry. These definitions primarily differ in what is meant by the term "ready." The comparison technique must contain a term which measures the "availability" of a piece of equipment without being ambiguous, yet meeting the functional requirements of the existing data systems.

An alternate approach to measure "availability" has been taken in the comparison technique to overcome the many definitions of "ready." This approach is to measure "availability" as the time a piece of equipment will operate before it is forced to shut down despite an existing operating schedule, (*i.e.*, the operating time between forced outages). Mathematically this approach will be described in greater detail in the following section and in Appendix A. This measure of availability is, however, not sufficient by itself to complete a meaningful comparison.

The effort required to achieve a given performance from a piece of equipment is as important as the given performance itself. Utility equipment which requires constant attendance is significantly less attractive than equipment which runs forever without repair or attendance. In the real world, operating equipment usually lies somewhere between no attention and constant attention. It is a measure of the attention expended to achieve performance which the comparison technique must include.

A term which includes a learning curve or learning function should be included. A learning function has for years been applied to manufacturing operations, design adequacy, student repetition, etc., to allow for time necessary to reach proficiency. A similar analogy is just as applicable to the design of utility equipment, the design of a utility plant, the installation or construction of the equipment or plant, and the equipment or plant operation. Near the completion of a project, personnel involved with each of these areas will normally admit that if they were to do the project again, modifications or changes would be made to improve the product. This is the learning curve as applied to the comparison technique.

Unfortunately, many of the major components and many of the station designs are one of a kind. Historically, this has been the nature of the utility business. Only recently (within the past 5 years or so) has the concept of a baseline central station electric plant, modified for specific site requirements, come into being. Thus, the learning curve for major components and for plant design has been generally limited to less than 5 replications by any individual vendor, designer, constructor, or operator. The fifth replication can, however, represent a significant operational improvement over the first if sufficient time elapses between each replication for intelligent modifications to be applied and tried.

A corallary to the benefit achieved from the learning curve, is the concept that some modifications can economically be incorporated into the first model reflecting beneficial changes incorporated in later replications. However, in most cases, the first model will never achieve the operating characteristics of the later models.

The learning function must become an integral portion of a comparison model. To compare the operating characteristics of a fifth model or replication to a first of its' kind edition must account for an anticipated learning function.

4.2 MODEL DESCRIPTION

The comparison model or Figure of Merit incorporates the following elements:

a) Existing data is applicable.

b) New data, if required, is not difficult to obtain.

c) The comparison technique is relatively simple to compute and apply.

d) The comparison technique includes the following:

    1) "Mechanical availability
    2) Maintenance/economic measure
    3) Scale-up or learning function

The comparison model computes a Figure of Merit from a three term equation. The first term in the equation is a measure of the probability of being operational at the end of a time period without "failure." The second term is a measure of the effort expended in completing a repair. The third term is a learning function which accounts for the number of replications of a unit or equipment item.

In mathematical terms the comparison model is:

$$\text{Figure of Merit} = \exp \underbrace{\left[-\lambda t e^{-\phi\tau}\right]}_{\text{I}} \underbrace{\left[\text{RMA}\right]}_{\text{II}} \underbrace{\left[\frac{i}{i + 1.0}\right]}_{\text{III}}^{-(0.6)}$$

where λ = The reciprocal of the mean time between full forced outages (1.0/hr).

t = Time period to be considered, (nominally 720 hrs in this study).

ϕ = The reciprocal of the mean time to repair a forced outage (1.0/hr).

τ = Time period allowed for repair of an outage before a failure is declared. (60 hrs in this study)

e = 2.718, the base of natural logarithms.

RMA = Relative Mechanical Availability, %, as defined by the Edison Electric Institute and set forth in Appendix A to this report.

i = The number of replications of a piece of equipment or plant. A replication is further restricted such that sufficient time is available to try one model and incorporate changes in the next prior to placement into service.

The Roman numerals designate the three terms in the Figure of Merit equation.

Term I defines the probability that a piece of equipment (or plant) will be functioning at the end of time period t with the additional constraint that repairs are allowed, but no repair or maintenance action requiring longer than τ hours to complete is operationally permissible. Term II, Relative Mechanical Availability (RMA), is a form of operating availability adjusted to show relative effort expended to reduce outage time. Term III is a derived learning function. A detailed derivation of each of these terms is presented in Appendix A to this report. Only a discussion of the reasoning and the limitations will be presented in this portion of the report.

4.3 MODEL DISCUSSION

The Figure of Merit, calculated by the formula presented in Section 4.2 of this report, has no physical significance by itself. The number calculated should not be interpreted in any manner other than a relative number used for comparison of one piece of operating equipment to another. Terms I and II do have physical significance as individual terms, their product does not.

Each of the terms in the computation of the Figure of Merit fulfills one of the design objectives set forth in Section 4.1, objective (4). The combination of these terms in product form was selected such that equal weight is given to each of the three areas of concern.

4.3.1 Discussion of Term I

The first term in the Figure of Merit equation comes from the reliability theory. A detailed derivation of this term can be found in Appendix A to this report. The portion of the term, $e^{-\lambda t}$, is the "reliability" or the probability that a piece of equipment will be functioning at the end of a specified time period, t. However, the demand for electical generation capacity fluctuates on daily, weekly, monthly, and yearly cycles. This demand, coupled with other system parameters suggests that there are periods of time wherein repairs and maintenance are permissible without sacrifice when a piece of equipment does not function during the entire time period, t. Thus, the concept arises that "reliability" can be modified to permit repairs and maintenance which do not exceed a given repair time, τ. The second exponential in Term I, $e^{-\phi\tau}$, performs the modification to the "reliability" to permit limited repairs or maintenance. Term I, thus, defines the probability that a piece of equipment will be functioning at the end of time period t, or that it can be repaired or maintained in time τ and returned to a functional status. This definition and approach approximates the real behavior and operation of equipment used in the electric utility industry.

Equipment which requires cyclic short-term maintenance such as zeolite bed regeneration for 2 hours every 24 hours is not classified "unreliable." Likewise, the spreader stoker which breaks a connecting link two or three times a month but which can be repaired in 30-minutes is by this definition not classified "unreliable." These are problems with which each utility must contend and face, but do not enter into this comparison model.

The characteristic time λ, the reciprocal of the mean time between full forced outages, has been selected to be identical with the definition set forth by the Edison Electric Institute (EEI) (ED-058) and reported in their annual Equipment Availability Report compiled by the Prime Movers Subcommittee. By EEI definition, a forced outage is "the occurrence of a component failure or other condition which requires that the unit be removed from service immediately or up to and including the very next weekend." The mean time between full forced outage was intentionally selected as the characteristic operating time rather than the mean time between partial forced outages. The data reporting and collection network for full outages appears to be much more accurate and complete than the data for partial forced outages.

The parameter ϕ, the reciprocal of the mean time to repair or restore a full forced outage, was selected to be identical with the EEI definition of forced outage hours. This selection was made following the same line of reasoning as was used to select the mean time between full forced outages with the additional constraint that the mean time to repair and the mean time between failures should be based on the same definition of "failure" or malfunction.

4.3.2 Discussion of Term II

Term II, Relative Mechanical Availability, in the Figure of Merit equation is an EEI defined term. This is a form of operating availability adjusted to show the relative effort needed to repair equipment which is in an outage status. One of the prime assumptions in deriving this term is that outage time is predominately affected by work schedules and crew sizes. Relative Mechanical Availability (RMA) uses manhours worked as a measure of effort. This effort is reasonably independent of work schedules. A detailed discussion of RMA is presented in Appendix A to this report.

4.3.3 Discussion of Term III

Term III in the Figure of Merit computation is a measure of the benefit which may be obtained from replications of a given equipment type or of a given plant design. The learning function is empirically derived from existing utility data. Some adjustment in the exponent may be warranted as additional data becomes available.

The highest difficulty in applying the learning function is to determine what constitutes a "new" model and what constitutes an "improved" model. The following definition will help overcome this difficulty. An improved model must be sufficiently later than the new model in time to permit the incorporation of changes which result from experience gained in any or all three of the following areas: manufacture, installation, and operation. Ideally, information from all three areas will be incorporated into an improved model.

SECTION 5

UTILITY COMPONENT OPERATING DATA

Performance data for equipment used in the electric utility industry have been collected on a continuing basis since 1965. There are at least four major data banks within the United States, each with its own definitions, data reporting systems and areas of interest. These systems conflict with each other and duplicate many areas, and as an aggregate sum, do not provide sufficient information in a form useful to this study.

An ad hoc steering committee has been set up by the American National Standards Institute to coordinate a data gathering effort. A consistent format is being developed for reporting and disseminating reliability data on equipment used in both the fossil and nuclear portions of the electric utility industry. Additionally, EPRI has several programs underway to define data needs. The existence of these programs highlights the present state of flux of the electric utility operating performance data acquisition and dissemination systems.

5.1 DEFINITION OF TERMS

Unless specifically stated otherwise, the terms used in this section are in accordance with the Edison Electric Institute (EEI) standard definitions.

Available: The status of a unit or major piece of equipment which is capable of service, whether or not it is actually in service.

Availability: The fraction of time that a unit or major piece of equipment is capable of service, whether or not it is actually in service.

Forced Outage: The occurrence of a component failure or other condition which requires that the unit be removed from service immediately or up to and including the very next weekend.

Forced Outage Hours (FOH): The time in hours during which a unit or major equipment was unavailable due to a forced outage.

Forced Outage Rate (FOR): The ratio of forced outage hours divided by service hours plus forced outage hours expressed as a percentage. FOR = FOH/(SH + FOH) x 100

Relative Mechanical Availability (RMA): Relative Mechanical Availability is a form of availability adjusted to show relative maintenance effort. A more complete definition is presented in Appendix A.

5.2 SOURCES AND AVAILABILITY OF DATA

There are four primary systems in operation in the United States which collect and report utility system performance data. These systems are the Edison Electric Institute (EEI) Prime Movers Committee; the Nuclear Plant Reliability Data System (NPRDS) under the direction of the American National Standards Institute (ANSI) subcommittee N18-20; the Gray Book I, issued by the Nuclear Regulatory Commission (NRC Gray Book); and the Federal Power Commission (FPC). The FPC publishes special reports on many different facets of the electric utility industry but does not issue routine reports on equipment components. The NRC Gray Book publishes performance data on the reactor systems for nuclear plants.

The NPRDS System is concerned with reliability-type data for the components in the nuclear safety systems of nuclear central station electric units. The EEI data is the only major data bank which is directly applicable to this study (*i.e.*, major utility equipment performance data). These data are published in the EEI Prime Movers Committee Reports (ED-058).

In addition to the four data sources previously mentioned, equipment performance data are scattered throughout the open literature, in many different journals, and in government reports. Most notable of the latter is WASH 1400, Reactor Safety Study-An Assessment of Accident Risks in U.S. Commerical Nuclear Power Plants (US-391). Additional data are recorded and maintained by many individual utilities, and by insurance companies. Much of the data in the open literature were not applicable to this study because of the short time spans reported or because of incomplete data sets. Insurance Company data covers only major outages above the policy deductibles and does not contain operating time, thus is not useful in this study.

It became evident that the EEI reports contained the longest time span of relevant data for the purposes of this study. EEI was commissioned to perform a computer search of their data base to provide Radian with year-by-year performance data of the information published in their ten year equipment availability summary. The results of this search are presented in Section 5.3.1.

5.3 UTILITY DATA PRESENTATION

The majority of performance data for electric utility component equipment presented in this section was obtained from three sources: 1) EEI reports and commissioned EEI data searches, 2) private utility files, and 3) the open literature. The EEI data presented such parameters as mean time between full forced outages, mean time to repair full forced outages, and relative mechanical availability. The private utility files provided only "availability" data. The open literature provided isolated data points, which could be applied only after careful verification of the definition of terms and their application.

The data necessary to describe existing electric utility system equipment, to the degree necessary for a meaningful comparison with FGD systems, exists within the EEI data system. The first search from this data bank was extremely useful, but did not provide all the requirements for this comparison. The data needed to address the "learning curve" hypothesis for the various utility equipment components was obtained in a second search.

In addition to the above sources, some data were excerpted from the technical literature to illustrate the effects of an apparent "learning curve." These data are for specific units of one utility and represent essentially one system design duplicated three times.

5.3.1 EEI Data Summary

EEI Data are presented for controlled circulation boilers, once-through circulation boilers, single shaft generators, tandem compound and cross compound turbines, and gas turbines. Data for the first five equipment items are presented from a special data search. The gas turbine data are from the annual equipment availability report of the Prime Movers Committee.

Operating data for controlled circulation boilers along with computed parameters, such as Term I and the product of Term I and II of the Figure of Merit are presented in Table 5-1. Controlled circulation boilers represent some of the oldest integral pieces of equipment used in central electric generating stations. In general, this equipment has an excellent performance history. The Term I-Term II product of the Figure of Merit is better than 50 for 390 MW and larger size boilers. The mean time between full forced outages is nominally longer than 1000 hours, whereas the mean time to repair

TABLE 5-1. OPERATING STATISTICS OF CONTROLLED CIRCULATION BOILERS

Years[1] Service	Units[1] in Service	Oper[1] Avail %	MTBFFO[1,2] Hrs	RMA[1,3] %	RMA[1,4] Units	FOH[1,5] Hrs/ Yrs	No. FO[1,6] Occur's per Yr.	MTTRFFO[7] Hrs	Figure of Merit[8] Term I	Figure of Merit[8] Term IxII
390 MW Thru 599 MW										
1	25	83.2	1441.10	88.7	14	274.0	6	46	.873	77.4
2	30	87.8	1355.4	81.9	19	216.6	6	36	.905	74.1
3	28	87.5	1371.5	86.6	18	221.7	6	37	.901	78.0
4	27	87.5	1344.4	70.6	16	399.1	6	67	.804	56.8
5	27	85.2	1051.6	63.5	15	437.1	8	55	.795	50.5
6	23	86.6	950.8	86.9	13	401.7	9	45	.819	71.2
7	16	85.1	834.9	65.1	11	462.9	10	46	.791	51.5
8	13	81.4	843.9	48.7	7	476.4	10	48	.783	38.1
9	13	81.5	572.6	79.1	4	683.1	15	46	.711	56.2
10	9	81.2	691.8	81.5	1	625.3	13	48	.742	60.5
600 + MW										
1	8	89.9	762.0	84.6	4	470.6	11	43	.791	66.9
2	9	80.6	1159.8	86.9	3	469.6	7	67	.776	67.4
3	9	85.8	1066.1	93.4	3	361.5	8	45	.837	78.2
4	6	86.0	1460.7	71.7	2	353.0	6	59	.837	60.0
5	4	76.0	1523.5	75.7	2	567.1	6	94	.779	59.0
6	3	77.0	1051.2	99.4	1	325.4	9	41	.853	84.8
7	2	84.6	1096.5	--	0	202.0	8	25	.942	--
8	1	75.4	486.7	--	0	85.5	17	5	1.00	--
9	1	99.1	2190.0	--	0	44.1	3	15	.994	--
10	1	88.3	1752.0	--	0	38.4	4	10	.999	--

---

[1] Reported by EEI for special request.

[2] MTBFFO-Mean time between full forced outage.

[3] RMA-Relative mechanical availabilty.

[4] RMA Units-Number of units which reported RMA data.

[5] FOH-Forced outage hours per year.

[6] No. FO-Number of forced outage occurences per year.

[7] MTTRFFO-Mean time to repair a full forced outage $= \frac{\text{FOH}}{\text{No. FO Occur.}}$

[8] Terms in computation of figure of merit from Section 4.0 of this report.

a full forced outage is less than 70 hours with one exception, the 600 Mw-and-above size class in its fifth year of service. These data indicate that, on the average, a controlled circulation boiler will operate for 42 days without experiencing a full forced outage and repair of the outage will take less than 3 days.

Operating statistics for once-through circulation boilers are presented in Tables 5-2 and 5-3. Once-through circulation boilers represent a much newer boiler type than the controlled circulation boiler. Supercritical boiler operating data are presented in Table 5-2 and subcritical operating data are presented in Table 5-3.

Once-through boilers represent the majority of new 390 MW and larger units which are currently being installed. This is illustrated by the number of once-through boilers which were in their tenth year of service (7) as compared to the number that were in their first year of service (94). The Term I-Term II product of the Figure of Merit of once-through boilers is 50 or greater with the exception of the 600 MW-and-above subcritical size of boiler. Based on the number of units reporting data, the once-through subcritical boiler represents a piece of equipment the utility industry has tried and has not accepted. (This boiler configuration was rejected for both operational and economic means.) The mean time between full forced outages is greater than 610 hours with three exceptions; the 600 MW-and-above subcritical class for the eighth, ninth, and tenth year of operation. The mean time to repair a full forced outage of a once-through boiler is nominally 80 hours. These data indicate that, on the average, a once-through boiler will operate 25 days without a full forced outage, and repair of the outage will take just over 3 days.

Single shaft generator operating statistics are presented in Table 5-4. The nominal Term I of the Figure of Merit for these generators is greater than 93. The mean time between full forced outages is greather than one

TABLE 5-2. OPERATING STATISTICS OF ONCE-THROUGH SUPER CRITICAL BOILERS

Years[1] Service	Units[1] in Service	Oper[1] Avail %	MTBFFO[1,2] Hrs	RMA[1,3] %	RMA[1,4] Units	FOH[1,5] Hrs/Yrs	No. FO[1,6] Occur's per Yr.	MTTRFFO[7] Hrs	Figure of Merit[8] Term I	Term IxII
390 MW Thru 599 MW										
1	36	86.8	1181.9	91.8	22	301.5	7	43	.860	78.9
2	37	86.8	1467.6	91.3	24	292.8	6	49	.866	79.1
3	34	83.3	1342.1	86.7	18	405.8	7	58	.826	71.6
4	35	85.3	1267.9	95.8	15	538.0	7	77	.771	73.9
5	38	80.9	1359.7	90.0	13	572.1	6	95	.755	68.0
6	34	79.9	1273.2	85.6	5	583.8	7	83	.760	65.1
7	28	83.3	1370.4	72.1	2	518.7	6	86	.770	55.5
8	18	84.3	1336.9	86.6	4	423.3	7	60	.820	71.0
9	8	80.1	1208.3	90.8	3	402.7	7	57	.812	73.7
10	3	83.9	1194.5	--	0	505.5	7	72	.770	--
600 + MW										
1	51	83.7	716.8	79.1	19	632.0	12	53	.723	57.2
2	46	83.9	992.9	84.1	15	580.6	9	64	.753	63.3
3	40	83.8	825.0	72.9	8	752.9	11	68	.697	50.8
4	32	81.0	776.7	84.9	5	837.5	11	76	.655	55.6
5	17	82.4	702.7	81.6	1	770.2	12	64	.669	54.6
6	11	72.8	688.5	--	0	677.2	13	52	.719	--
7	6	79.2	730.0	--	0	626.8	12	52	.733	--
8	3	92.9	1095.0	--	0	348.5	8	44	.845	--
9	1	77.1	876.0	--	0	425.1	9	47	.795	--

[1] Reported by EEI for special request.

[2] MTBFFO-Mean time between forced outage.

[3] RMA-Relative mechanical availability

[4] RMA Units-Number of units which reported RMA data.

[5] FOH-Forced outage hours per year.

[6] No. FO-Number of forced outage occurences per year.

[7] MTTRFFO-Mean time to repair a full forced outage = $\frac{\text{FOH}}{\text{No. FO Occur}}$

[8] Terms in computation of figure of merit from Section 4.0 of this report.

TABLE 5-3. OPERATING STATISTICS OF ONCE-THROUGH SUBCRITICAL BOILERS

Years[1] Service	Units[1] in Service	Oper[1] Avail %	MTBFFO[1,2] Hrs	RMA[1,3] %	RMA[1,4] Units	FOH[1,5] Hrs/ Yr	No.FO[1,6] Occur's per Yr	MTTRFFO[7] Hrs	Figure of Merit[8] Term I	Figure of Merit[8] Term IxII
390 MW Thru 599										
1	3	84.0	1194.5	89.5	2	462.1	7	66	.784	70.2
2	3	83.8	797.1	88.4	2	393.1	11	36	.843	74.5
3	2	81.3	1347.7	78.5	1	464.2	6	77	.783	61.5
4	2	79.8	1460.0	83.0	2	192.4	6	32	.927	76.9
5	2	91.3	1347.7	95.0	2	135.6	6	23	.961	91.3
6	2	85.0	1952.0	85.9	2	287.7	4	72	.852	73.2
7	2	85.1	2920.0	87.7	2	132.3	3	44	.939	82.4
8	2	81.9	8760.0	76.8	1	44.3	1	44	.979	75.2
9	2	84.3	922.1	89.7	2	511.1	9	57	.761	68.3
10	1	63.0	798.5	--	0	983.1	10	98	.613	--
600 + MW										
1	4	68.9	974.0	47.6	2	312.3	9	35	.875	41.7
2	6	73.7	1546.0	48.9	4	659.6	6	110	.764	37.4
3	5	83.7	1018.6	72.6	4	544.2	8	68	.764	54.2
4	5	77.1	1043.4	51.3	3	470.6	8	59	.779	40.0
5	5	78.6	843.7	70.4	2	546.6	10	55	.751	52.9
6	4	78.1	614.7	49.0	2	599.0	14	43	.748	36.7
7	4	65.8	661.1	12.8	2	748.8	13	58	.679	8.7
8	3	69.7	597.3	64.9	2	1068.7	14	76	.578	37.5
9	2	75.9	501.9	--	0	957.1	17	56	.611	--
10	2	73.3	473.5	--	0	1410.9	18	78	.494	--

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[1] Reported by EEI for special request.

[2] MTBFFO-Mean time between full forced outage.

[3] RMA-Relative mechanical availability.

[4] RMA Units-Number of units which reported RMA data.

[5] FOH-Forced outage hours per year.

[6] No. FO-Number of forced outage occurences per year.

[7] MTTRFFO-Mean time to repair a full forced outage $= \frac{\text{FOH}}{\text{No. FO Occur.}}$

[8] Terms in computation of figure of merit from Section 4.0 of this report.

TABLE 5-4. OPERATING STATISTICS OF SINGLE SHAFT GENERATORS

Years[1] Service	Units[1] in Service	Oper[1] Avail %	MTBFFO[1,2] Hrs	FOH[1,3] Hrs/ Yrs	No. FO[1,4] Occur's per Yr.	MTTRFO[5] Hrs	Figure of[6] Merit Term I
390 MW Thru 599 MW							
1	67	94.0	9625.6	38.0	1	38	.985
2	72	93.8	15777.0	44.3	1	44	.988
3	56	91.2	18878.8	123.8	0	--	.962
4	54	95.4	26296.0	27.5	0	--	.973
5	51	92.9	17191.4	17.2	0	--	.959
6	41	94.9	21134.1	33.0	0	--	.966
7	29	95.7	28232.0	3.6	0	--	.975
8	19	93.0	20808.0	3.7	0	--	.966
9	8	99.6	35040.8	0.5	0	--	.980
10	3	79.2	65700.0	51.1	1	51	.967
600 + MW							
1	54	90.2	9457.7	174.9	1	175	.941
2	48	90.3	9247.5	293.1	1	293	.933
3	40	95.1	14608.0	82.9	1	83	.976
4	30	93.9	21906.0	172.9	0	173	.977
5	16	95.1	15576.0	72.4	1	72	.980
6	9	94.3	13140.0	17.4	1	17	.998
7	4	99.2	8760.0	14.4	1	14	.999
8	1	100.0	8760.0	0	0	--	.921

[1] Reported by EEI for special request.

[2] MTBFFO-Mean time between full forced outage.

[3] FOH-Forced outage hours per year

[4] No. FO-Number of forced outage occurrences per year.

[5] MTTRFFO-Mean time to repair a full forced outage $= \frac{\text{FOH}}{\text{No. FO Occurrences}}$

[6] Terms in computation of figure of merit from Section 4.0 of this report.

year, and the mean time to repair a full forced outage is less than 65 hours. These figures indicate that both the 600-MW-and-above class and the 390-MW-through-599-MW class single shaft generators should operate for a year without incurring a full forced outage.

The operating statistics for the tandem compound and cross compound turbine are presented in Table 5-5, 5-6, 5-7, and 5-8. Subcritical and supercritical turbines are included in both classes. Term I of the Figure of Merit of both classes of turbines is greater than 83. The mean time between full forced outages is longer than 6 months with an average repair time of four and one half years.

Term II in the Figure of Merit was not available for these turbines, and consequently the product of Term I and II is not reported.

The performance data on gas turbine units reported by EEI is presented in Table 5-9. No distinctions are made by EEI concerning the gas turbine size or age. The EEI data is probably weighted toward smaller, older gas turbines. The most recently reported availability for this class of equipment is 89.0 percent (ED-043).

Availability data were obtained from a private utility for several gas turbine units according to unit age. These data are plotted in Figure 5-1. As can be seen from this graph, the Term I-Term II product of the Figure of Merit for gas turbines is greater than 70 and the turbine availability tends to level off at approximately 90 percent after three or four years of operation. These figures are in agreement with the data reported by EEI.

In addition to the above data, the EEI annual report contained performance data on condensers. These data were not represented in tabular form because all data showed the condensers to have extremely high availabilities. The nominal mean time between full forced outages for this component was on the order of 2 to 3 years.

TABLE 5-5. OPERATING STATISTICS OF TANDEM COMPOUND SUBCRITICAL TURBINES

Years[1] Service	Units[1] in Service	Oper[1] Avail %	MTBFFO[1,2] Hrs	FOH[1,3] Hrs/ Yrs	No. FO[4] Occur's per Yr.	MTTRFFO[5] Hrs	Figure of[6] Merit Term I.
390 MW Thru 599 MW							
1	32	87.0	3549.0	291.5	2	146	.874
2	36	89.0	3756.6	103.0	2	52	.941
3	28	92.2	6294.2	66.3	1	66	.955
4	25	89.7	4762.4	191.3	2	96	.922
5	22	88.8	3933.6	132.0	2	66	.929
6	16	92.4	4524.4	112.1	2	56	.947
7	11	86.2	10712.0	7.8	1	8	1.00
8	10	92.7	12517.7	87.7	1	88	.971
9	7	93.3	8760.0	14.1	1	14	.999
10	4	84.0	3187.6	67.0	3	22	.985
600 + MW							
1	13	84.4	2712.6	247.5	3	83	.879
2	13	84.5	3452.4	227.0	2	114	.884
3	11	88.2	5669.6	34.3	1	34	.978
4	8	89.0	6375.3	148.1	1	148	.927
5	7	91.7	12268.8	8.4	1	8	1.00
6	4	91.0	3504.0	13.8	2	7	1.00
7	3	93.3	2920.0	81.7	3	27	.974
8	1	100.0	8760.0	0	0	--	.921

[1] Reported by EEI for special request.

[2] MTBFFO-Mean time between full forced outage.

[3] FOH-Forced outage hours per year.

[4] No. FO-Number of forced outage occurrences per year.

[5] MTTRFFO-Mean time to repair a full forced outage $= \frac{\text{FOH}}{\text{No. FO Occurrences}}$

[6] Terms in computation of figure of merit from Section 4.0 of this report.

TABLE 5-6. OPERATING STATISTICS OF TANDEM COMPOUND SUPER CRITICAL TURBINES

Years[1] Service	Units[1] in Service	Oper[1] Avail %	MTBFFO[1,2] Hrs	FOH[1,3] Hrs/ Yr	No. FO[4] Occur's per Yr.	MTTRFFO[5] Hrs	Figure[6] of Merit Term I.
390 MW Thru 599 MW							
1	32	85.8	4007.0	413.5	2	207	.874
2	32	82.3	4065.0	359.5	2	180	.881
3	26	87.4	5556.9	514.9	2	257	.902
4	28	93.8	5987.7	50.4	1	50	.964
5	28	88.8	5578.4	110.9	2	55	.958
6	24	90.6	5392.0	36.4	2	18	.995
7	18	87.8	5437.2	125.8	2	63	.950
8	9	89.8	8760.0	190.3	1	190	.942
600^+ MW							
1	42	89.0	2673.2	197.4	3	66	.897
2	36	86.6	3219.2	276.9	3	92	.890
3	30	93.8	4174.1	97.5	2	49	.951
4	22	92.0	3323.2	313.1	3	104	.885
5	9	83.1	3583.6	488.1	2	244	.855
6	5	94.2	7300.0	4.6	1	5	1.00
7	1	64.9	1752.0	70.3	4	18	.985
8	2	93.6	2502.9	124.9	3	42	.933

[1] Reported by EEI for special request.

[2] MTBFFO-Mean time between full forced outage.

[3] FOH-Forced outage hours per year.

[4] No. FO-Number of forced outage occurrences per year.

[5] MTTRFFO-Mean time to repair a full forced outage $= \frac{\text{FOH}}{\text{No. FO Occur.}}$

[6] Terms in computation of figure of merit from Sec. 4.0 of this report.

TABLE 5-7. OPERATING STATISTICS OF CROSS COMPOUND SUBCRITICAL TURBINES

Years[1] Service	Units[1] in Service	Oper[1] Avail %	MTBFFO[1,2] Hrs	FOH[1,3] Hrs/ Yrs	No. FO[4] Occur's per Yr	MTTRFFO[5] Hrs	Figure[6] of Merit Term I.
390 MW-599 MW							
1	5	79.2	10956.0	25.2	1	25	.994
2	8	91.0	6373.1	126.8	1	127	.932
3	7	90.6	6816.0	150.6	1	151	.931
4	10	92.9	12517.7	9.6	1	10	1.00
5	11	92.0	8036.0	95.9	1	96	.953
6	11	96.1	8036.0	17.0	1	17	.997
7	11	91.0	6888.0	40.8	1	41	.976
8	9	87.2	15772.9	2.3	0	--	.955
9	10	90.8	2504.9	61.6	3	20	.986
10	9	83.9	5394.5	40.4	2	20	.993
600^+ MW							
1	1	93.7	2190.0	274.0	3	91	.844
2	3	91.9	5256.0	129.3	1	129	.918
3	3	85.8	26304.0	0	0	--	.973
4	3	90.1	26280.0	0	0	--	.973
5	3	78.0	26328.0	0	0	--	.973
6	3	89.2	5256.0	189.3	1	189	.905
7	3	81.6	6576.0	147.5	1	148	.930
8	3	80.4	5256.0	280.7	1	281	.895
9	3	89.9	8776.0	215.1	1	215	.940
10	3	88.5	26280.0	0	0	--	.973

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[1] Reported by EEI for special request.
[2] MTBFFO-Mean time between full forced outage.
[3] FOH-Forced outage hours per year.
[4] No. FO-Number of forced outage occurrences per year.
[5] MTTRFFO-Mean time to repair a full forced outage =
[6] Terms in computation of figure merit from Section 4.0 of this report.

TABLE 5-8. OPERATING STATISTICS OF CROSS COMPOUND SUPER CRITICAL TURBINES

Years[1] Service	Units[1] in Service	Oper[1] Avail %	MTBFFO[1,2] Hrs	FDH[1,3] Hrs/ Yrs	No. FO[4] Occur's per Yr.	MTTRFFO[5] Hrs	Figure[6] of Merit Term I
390 MW Thru 599 MW							
1	4	93.2	2697.2	319.5	3	107	.859
2	6	91.4	5845.3	39.2	1	39	.974
3	7	93.0	6134.4	245.4	1	245	.912
4	6	93.3	13146.0	69.5	1	70	.977
5	9	89.7	11269.7	53.5	1	54	.979
6	9	89.0	9861.0	45.2	1	45	.981
7	9	91.4	19716.0	138.0	0	--	.964
8	8	88.1	6377.5	557.8	1	558	.904
9	6	92.0	10512.0	18.2	1	18	.998
10	3	97.0	26280.0	0	0	--	.973
600 + MW							
1	15	87.2	1603.6	193.6	5	39	.908
2	15	87.8	1752.9	384.5	5	77	.828
3	13	93.3	2279.0	92.8	4	23	.977
4	11	91.5	4017.0	155.4	2	78	.920
5	9	92.8	4930.5	213.6	2	107	.920
6	7	85.5	4718.8	97.8	2	49	.956
7	5	98.0	3981.81	69.2	2	35	.968
8	3	99.6	6570.0	24.3	1	24	.991
9	1	77.7	2190.0	345.3	3	115	.823

[1] Reported by EEI for special request.

[2] MTBFFO-Mean time between full forced outage.

[3] FOH-Forced outage hours per year.

[4] No. Fo-Number of ofrced outage occurrences per year.

[5] MTTRFFO-Mean time to repair a full forced outage $= \frac{\text{FOH}}{\text{No. FO Occur.}}$

[6] Terms in computation of figure merit from Section 4.0 of this report.

TABLE 5-9. OPERATING STATISTICS FOR GAS TURBINES

EEI reporting period	Units in service	Oper. avail. (%)	MTBFFO[1] (hrs)	RMA[2] (%)	No. units reporting RMA	FOH[3] (hrs/yr)	No. occurrences per yr	MTTRFFO[4] (hrs)	Figure of Merit[5]	
									Term I	Term I & II
1960-1972	432	90.6	784	97.7	138	406	10	40.6	.811	79.2
1964-1973	346	90.8	765	97.5	140	371	10	37.1	.830	80.9
1965-1974	565	89.0	807	97.6	139	503	10	50.3	.763	74.5

Source: ED-043, ED-057, ED-058

[1] MTBFFO - Mean Time Between Full Forced Outage

[2] RMA - Relative Mechanical Availability

[3] FOH - Forced Outage Hours

[4] MTTRFFO - Mean Time To Repair a Full Forced Outage

$$\frac{\text{FOH/yr}}{\text{No Occurrences per Year}}$$

[5] Terms in computation of Figure of Merit from Sec. 4.0 of this report.

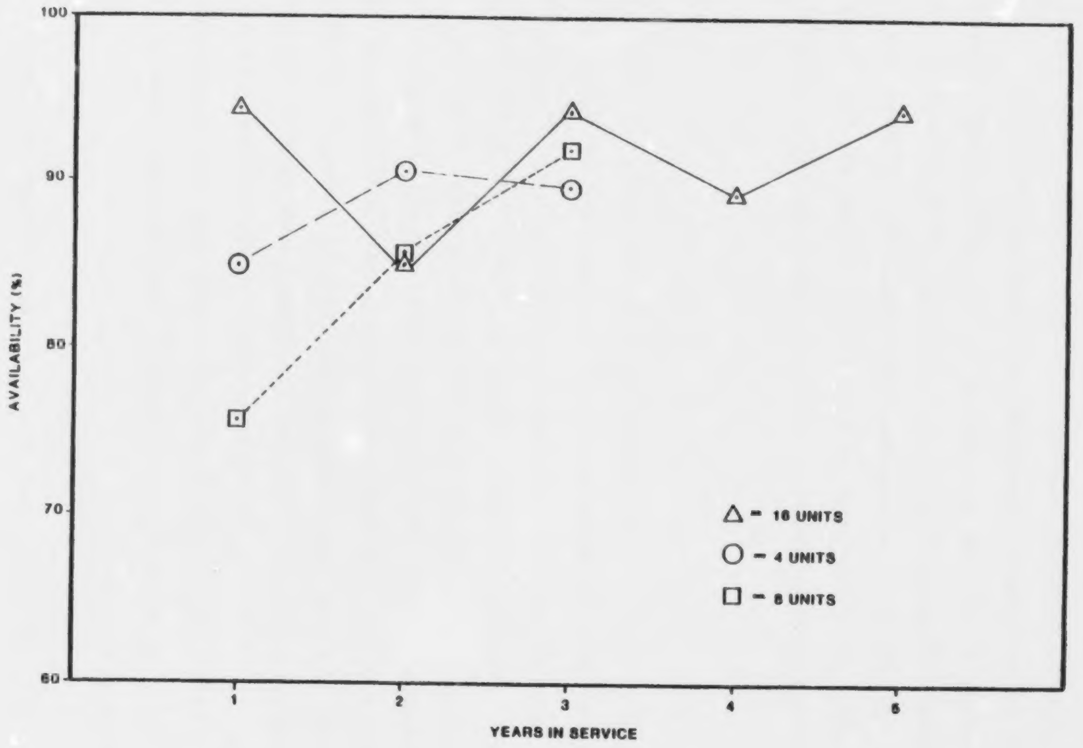

Figure 5-1. Availability of gas turbines *vs*. years in service.

5.3.2 Replicate Unit Data

Data were obtained from the open literature which seem to show the trend of unit performance as a function of the "learning curve" for a series of essentially similar central station generating units. These power stations contain the same type of equipment, designed and constructed by one architectural/engineering firm. As the design of the generating station was repeated from the construction of Big Sandy 2 through Gavin 2, the forced outage rate for each of the units decreased significantly. Figure 5-2 shows forced outage rate as a function of plant life in months for these stations and seems to illustrate validity of the "learning curve" hypothesis.

5.4 DATA TRENDS

The "learning curve" that has been hypothesized to apply to central electrical generating stations, and appears to be supported by data as shown in Figure 5-2, also is supported by data on individual pieces of equipment in the generating system. The three phases shown in Figure 5-3 represent the typical performance during the life of a piece of equipment. Phase I, the early failure or "burn-in" phase, reflects the early troubles which often arise with mechanical devices. During the second phase, which may be termed the "useful life," the failure rate remains essentially constant or follows a relatively slow change in value. Utility equipment components demonstrate availability between 70 to 90 percent during their useful lives. Phase III, the wear-out phase, illustrates the effects of aging when the equipment begins to wear out. A comprehensive maintenance program can, however, delay the occurrence of this phase.

In contrast to the data presented for power generating stations describing a "learing curve" and the apparent logic in the three phases of the individual pieces of equipment, the data presented in this report consist of composite totals and do not clearly show a "learning effect." As presented in Figure 5-4, fluctuation in Term I of the Figure of Merit for boilers and turbines on a composite basis do not follow the failure rate diagram presented

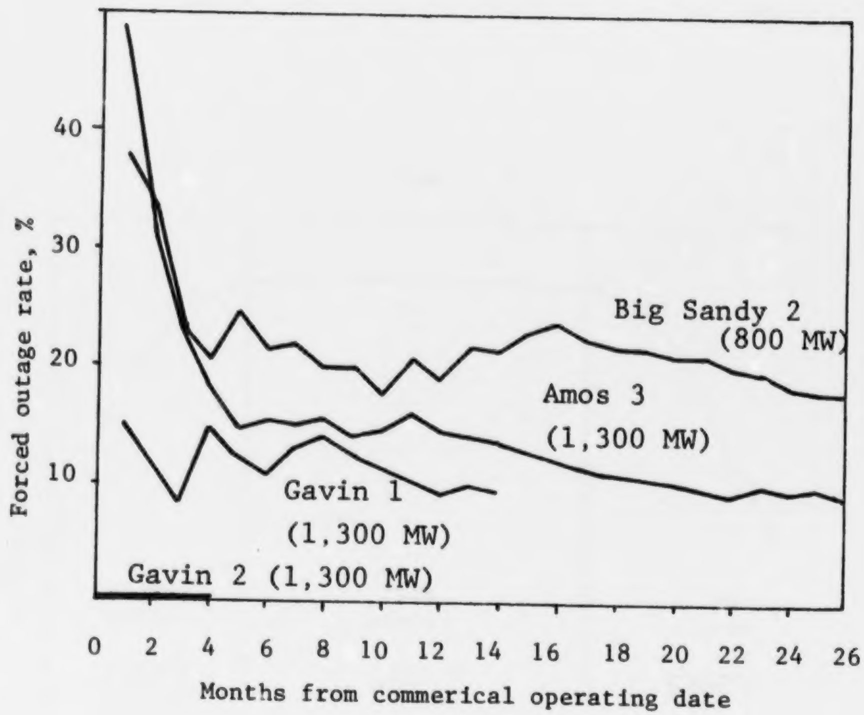

Figure 5-2. Forced-outage rates for three 1,300-MW units plus 800-MW Big Sandy 2.

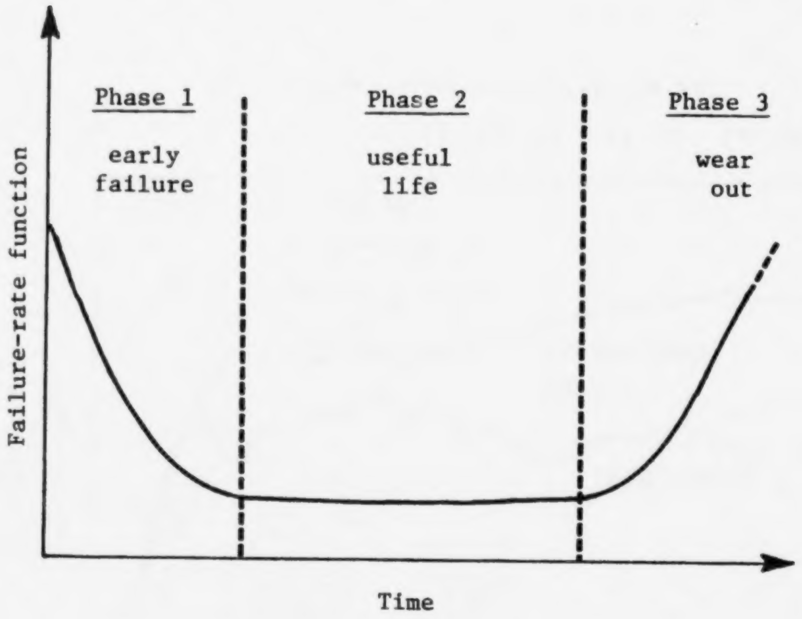

Figure 5-3. Typical failure-rate characteristic for engineering devices.

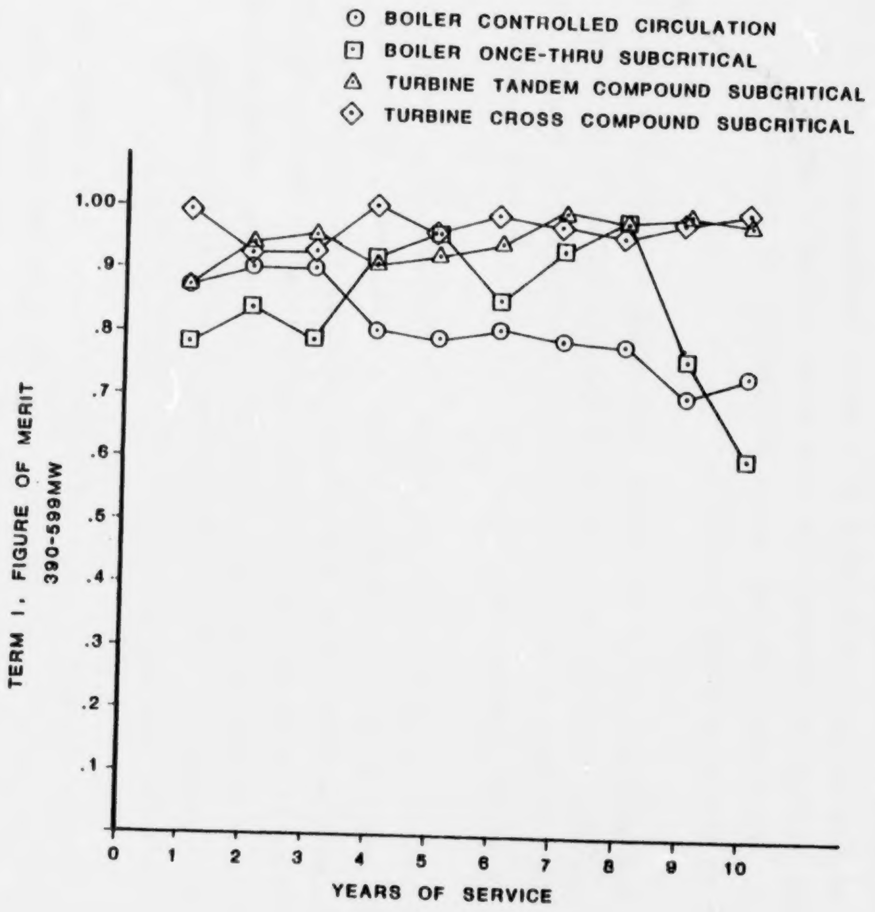

Figure 5-4. Equipment Maturity.

in Figure 5-3. The data do not indicate a large variation in reliability until the third year of operation. After the third year, the reliability of each piece of equipment begins to vary significantly without indicating clear trend which would support the failure rate diagram.

It should be emphasized that these composite data do not necessarily contradict the failure rate diagram. It would seem valuable to obtain a large amount of data on individual units in order to further test the hypothesis. It could be that the failure rate diagram is blurred by the use of composite data. Thus, although the data do not support the failure rate diagram, they do not necessarily contradict it.

Data on the availability of the boiler in comparison with the availability of the entire unit has been plotted in Figures 5-5 and 5-6. These plots do not seem to support the "learning curve" theory in that overall unit availability is fairly constant over the first nine years of unit operation.

In addition, it is evident that the boiler is the equipment item which predominately controls unit availability. Thus, new equipment, added to a utility unit, must perform better than present boilers, if a degradation of unit availability is to be avoided. Further, the turbine is the second least available piece of equipment in a generating unit. Thus, new equipment added in series with a generating unit, which performs as well as the turbine, would not degrade the unit performance appreciably.

Finally, a very meaningful trend evidenced by the EEI data search was the significant decrease in the number of units reporting RMA data. Over 50 percent of the units were reporting RMA data in 1971. The number of units reporting RMA data has decreased to less than 10 percent of the operating units from 1972 to the present. Thus, the most recent values of RMA may not be representative. Although RMA is an optional reporting feature within the EEI data system, it is the only reported statistic that measures, even secondarily, the economics of repair/maintenance effort.

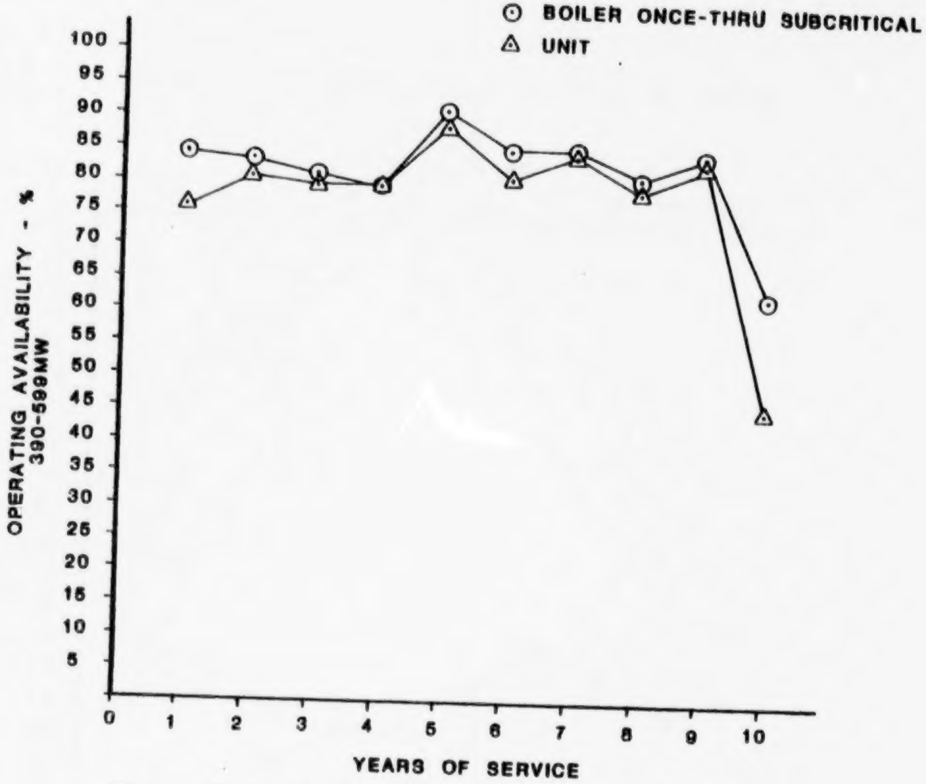

Figure 5-5. Boiler and unit maturity 390-599 MW

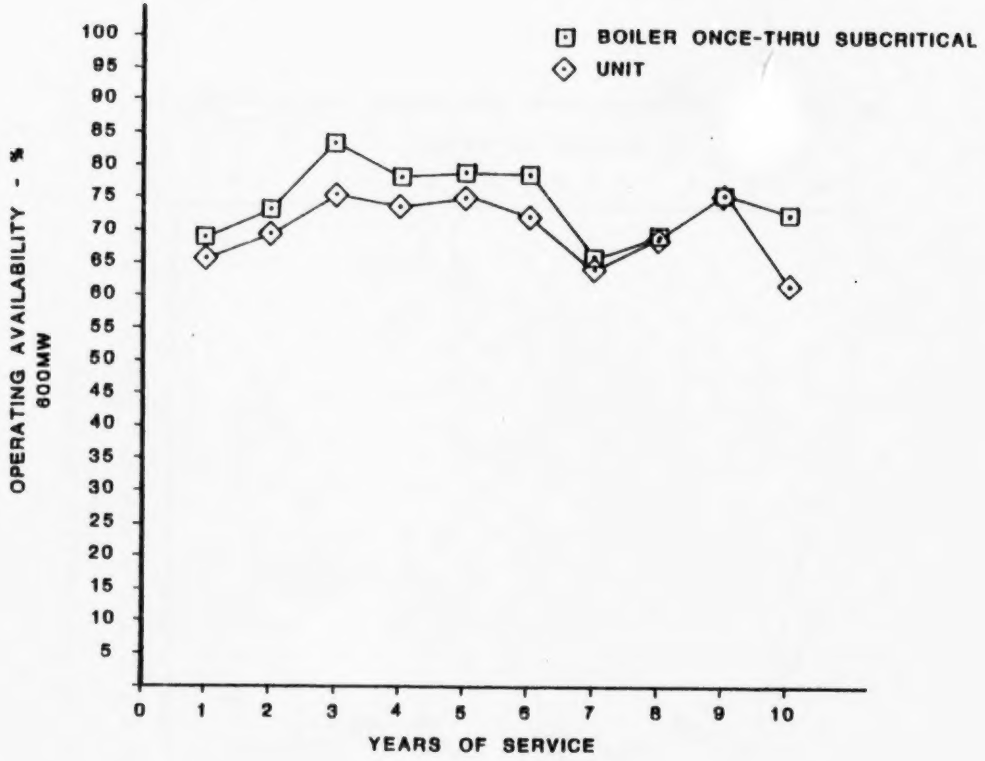

Figure 5-6. Boiler and unit maturity 600 MW

SECTION 6

FGD SYSTEM OPERATING DATA

Reliability data on operating FGD systems is scarce. At present the only recognized data bank on FGD systems is the PEDCo Summary Report - Flue Gas Desulfurization Systems (PE-227). The PEDCo report, which is prepared under EPA contract, provides a continual update of the status and performance of operational FGD systems. In addition, the report summarizes the status of FGD systems in the construction or planning stage.

There are currently no efforts underway to gather the type of data necessary to compare FGD system reliability to the reliability of other components in the power generation train. Specifically, the type of information which has traditionally been collected by EEI for boilers, turbines, condensers, etc., has not been gathered for FGD systems. However, EEI's 1976 revised Equipment Availability Data Reporting Instructions (ED-060) have been modified to include FGD systems.

6.1 DEFINITION OF TERMS

As discussed in Section 4.0, data on FGD system operations is limited. There are four parameters used by PEDCo in their bi-monthly FGD status reports which are commonly used in reporting FGD system operating data. These four parameters, as defined below, will be used in the following sections to report the FGD system operating data collected during this study.

1) $$\text{Availability} = \frac{\text{Hours the FGD system was available for operation}}{\text{Hours in the period}}$$

2) Reliability = $\frac{\text{Hours the FGD system was operated}}{\text{Hours the system was required to operate}}$

3) Operability = $\frac{\text{Hours the FGD system was operated}}{\text{Hours the boiler was operated}}$

4) Utilization = $\frac{\text{Hours the FGD system was operated}}{\text{Hours in the period}}$

6.2 SOURCES AND AVAILABILITY OF DATA

The major source of FGD system performance data presented in this report is the PEDCo Summary Report - Flue Gas Desulfurization Systems (PE-227). Unfortunately, this data is incomplete over the life of the six lime/limestone FGD systems identified in Section 3.2.2. Table 6-1 summarizes the performance data which is published in PEDCo's report. The table identifies which parameter is reported for each system and the time period for which the parameter has been reported.

TABLE 6-1. DATA AVAILABLE FROM PEDCo's FGD SUMMARY REPORT

System	Availability	Reliability	Operability	Utilization
Cholla		1/74 - 8/76		
Will County	3/75 - 7/76	3/75 - 7/76*	3/72 - 7/76	3/75 - 7/76
Phillips				7/75 - 3/76
LaCygne	1/75 - 8/76		1/74 - 12/74	
Green River	12/75 - 8/76	12/75 - 8/76	12/75 - 8/76	12/75 - 8/76
Paddy's Run			4/73 - 8/76	

*Reliability as calculated by PEDCo for Will County =

$$\frac{\text{Hours FGD System Operated}}{\text{Hours system operated + (Period hours - Available hours)}}$$

It is evident from Table 6-1 that there is no common parameter reported for all six systems. Operability is reported for four while availability, reliability, and utilization are reported for three of the six systems.

The following utilities were contacted in an effort to expand the available data base and to collect data for FGD systems similar to that which is reported by EEI for other utility components (*e.g.*, mean time between failures, mean time to repair and relative mechanical availability). However, it was discovered that the utilities which operate FGD systems do not collect this type of data. This reflects the fact that no standardized procedure currently exists for reporting FGD system reliability data. The utilities that were contacted are as follows:

1) Arizona Public Service Company (APS)
2) Commonwealth Edison Company (CE)
3) Duquesne Light Company (DL)
4) Kansas City Power and Light Company (KCP&L)
5) Kentucky Utilities Company (KU)
6) Louisville Gas and Electric Company (LG&E)

As a result of the contact with KU, American Air Filter Company (AAF) was contacted for information on the [illegible]en River FGD systems.

Several of the companies contacted asked for a written request for the information and/or data forms to fill out. Data forms were prepared which, if completed, would provide performance data on the FGD systems from start-up through the present (Figures 6-1 through 6-3). In addition, the completed forms would permit calculation of parameters such as mean time between failures, mean time to repair, and relative mechanical availability.

Only Commonwealth Edison and American Air Filter provided additional FGD performance data for this evaluation. Commonwealth Edison provided Radian with Monthly Progress Reports and Running Times and Outages for

FGD SYSTEM RELIABILITY INFORMATION

System ______________

Start-Up Date ______________

Number of Modules ______________

Size of Modules (ACFM) ______________

Total System Operating Hours ______________

Total Boiler Hours in Period for Which Data Is Available ______________

Total Hours System Was Required to Operate ______________

Total Hours System Was Available to Operate ______________

Longest Continuous System Operation ______________

Average Load on System per Operating Hour ______________

Maintenance Hours per Module per Week ______________

Figure 6-1. Data form 1.

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM ____________ MODULE ____________

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate

Figure 6-2. Data form 2.

FGD SYSTEM RELIABILITY INFORMATION

Failure Number	Date Of Failure	Module Down	Description of Failure	Percent Load At Failure	Estimated Time To Repair

Figure 6-3. Data form 3.

the Will County FGD System. These documents covered the time period from February 1972 through September 1976. American Air Filter provided availability, reliability, and operability data for the Green River FGD System for the period through September 1976. In addition, utilization data was provided for September 1975 through December 1976.

One additional source of performance data was a report prepared by Radian Corporation for the EPA. This report, entitled Review and Analysis of Louisville Gas and Electric Scrubbing System Data, contained nine months of utilization data for LG&E's Paddy's Run System.

Table 6-2 summarizes the performance data collected by Radian. These data do not provide any parameters in addition to those reported by PEDCo. However, the data do provide FGD performance information over a longer time period.

TABLE 6-2. DATA COLLECTED BY RADIAN

System	Availability	Parameter Reliability	Operability	Utilization
Cholla				
Will County	2/72 - 8/76		2/72 - 8/76	2/72 - 8/76
Phillips				
LaCygne				
Green River	12/75 - 9/76	12/75 - 9/76	12/75 - 9/76	9/75 - 9/76
Paddy's Run				4/73 - 12/73

Although the data collected results in a more complete performance history, the information is not comprehensive. Table 6-3 depicts the start-up data for each system and the date from which performance data is reported. For Will County, Green River and Paddy's Run, at least one parameter has been collected from the date of start-up. However, performance data for the other three systems did not begin until some point in time subsequent to the start-up date.

TABLE 6-3. PERFORMANCE DATA COLLECTION VS SYSTEM OPERATION

System	Start-up Date	Date Data Collection Began
Cholla	9/73	1/74
Will County	2/72	2/72
Phillips	8/73	7/75
LaCygne	6/73	1/74
Green River	9/75	9/75
Paddy's Run	4/73	4/73

The preceding discussion and table emphasize the requirement for an organized and standardized system for reporting FGD system reliability data. Section 8.0 contains recommendations for collecting the data required to determine FGD system reliability in comparison to utility component reliability.

6.3 DATA PRESENTATION

Data which report the performance of operating FGD systems is limited to the four parameters defined in Section 6.1. Table 6-4 illustrates average values for the performance data which have been reported for the FGD systems under consideration in this study. In addition, the time period covered by the reported data is shown. The supporting information which was used to calculate the averages presented in Table 6-4 can be found in Appendix C.

TABLE 6-4. FGD SYSTEM PERFORMANCE DATA - AVERAGE VALUES

			Availability	Reliability	Operability	Utilization
Cholla	-	Module A		92.2% (30 months)		
Will County	-	Module A	43.0% (53 months)		40.0% (53 months)	33.6% (53 months)
Will County	-	Module B	43.7% (31 months)*		21.0% (55 months)	16.4% (55 months)
Phillips	-	All Modules	***			61.3% (9 months)
LaCygne	-	All Modules	88.1% (17 months)		76.3% (10 months)**	
Green River			82.6% (10 months)	84.3% (10 months)	80.8% (10 months)	51.0% (13 months)
Paddy's Run	-	All Modules			41.8% (42 months)	28.3% (9 months)

---

* This value for availability does not include the 24 month period from 5/73 to 4/75 during which the system did not operate. (See Figure C-4 in Appendix C.)

** This value for operability is based on all seven scrubber modules. Therefore when fewer than seven are in service, operability is less than 100 percent.

*** Operating data provided after this report was issued.

As illustrated in Table 6-4, the average values of the performance parameters vary from one system to the next. The relationship between these average values and the value of each of the performance parameters applied to FGD systems as a class is not immediately evident. One method of interpreting the data in Table 6-4 is to apply statistical analysis and calculate a range in which the "true" value of an individual performance parameter lies.

Table 6-5 presents a range for each of the performance parameters. These ranges were determined on the basis of the average values in Table 6-4. According to simple probability theory, the "true" value of each of the four performance parameters should lie in the given ranges.

TABLE 6-5. RANGES FOR PERFORMANCE PARAMETERS

Parameter	Range %	Confidence Level
Availability	$30.2 \le A \le 100$	90%
	$0 \le A \le 100$	99%
Reliability	$63.2 \le R \le 100$	90%
	$0 \le R \le 100$	99%
Operability	$0 \le O \le 99$	90%
	$0 \le O \le 100$	99%
Utilization	$27.6 \le U \le 69.2$	90%
	$3.5 \le U \le 93.3$	99%

The following sample calculation details how the ranges presented in Table 6-5 were determined.

Availability = A

Will County = 43.35% Average Availabilities
LaCygne = 88.1 % Average Availabilities
Green River = 82.6 % Average Availabilites

Assuming measured FGD system availability is arrayed in a normal distribution about the "true" value of availability for FGD systems as a class, the following relationships apply (GR-255).

$$\hat{\sigma}^2 = \frac{1}{(n-1)} \sum_{j=1}^{n} (x_j - \hat{u})^2 \qquad (6\text{-}1)$$

$$(\hat{u} - t\frac{\hat{\sigma}}{\sqrt{n}}) \leq u \leq (\hat{u} + t\frac{\hat{\sigma}}{\sqrt{n}}) \qquad (6\text{-}2)$$

where

$\hat{\sigma}^2$ = The square of the standard deviation of a population estimated by the Bessel correction.

n = Number of samples taken, which in this application represents the number of systems that have reported data.

x_j = Individual value of each sample or the value of the performance parameter reported for a single system.

$\hat{u}$ = Estimate of the true value of a performance parameter which is the average of x_j's.

u = The "true" value of a performance parameter.

t = Variate of the Student's "t" distribution which is determined by the number of samples and the confidence level assigned to the range.

To calculate a range in which the true value of availability lies, set A = u and place a 90% confidence level on the range. Then,

$$\text{Average} = \hat{u} = \frac{43.35 + 88.1 + 82.6}{3} = 71.35$$

$$\hat{\sigma}^2 = \tfrac{1}{2}\left[(43.35 - 71.35)^2 + (88.1 - 71.35)^2 + (82.6 - 71.35)^2\right]$$

$$+$$

$$\hat{\sigma}^2 = \frac{784 + 280.6 + 126.6}{2}$$

$$\hat{\sigma}^2 = 595.6 \quad \hat{\sigma} = 24.4$$

From the Student's "t" test, "t" = 2.92

when n-1 = 2 and P = 95 (Probability value equivalent to a 90% confidence level).

Then

$$\left(71.35 - \frac{(2.92)(24.4)}{\sqrt{3}}\right) \leq A \leq \left(71.35 + \frac{(2.92)(24.4)}{\sqrt{3}}\right)$$

with 90% confidence

or

$$30.2 \leq A \leq 100$$

The preceding calculation is based on a normal distribution of performance parameters about a true value. Although this assumption may not represent the actual distribution of FGD system performance parameters, it is valid due to the small number of data points that currently exist.

Table 6-5 illustrates the fact that the performance data which is currently available is insufficient to permit a "true" determination of FGD system performance. The narrowest range is for utilization (20 percent) and if the confidence level is increased to 99 percent, all but the utilization parameter range expands to cover all possible values of the performance parameters (*i.e.*, 0 < parameter < 100).

6.4 DATA TRENDS

Based on the above discussion, it is evident that FGD system performance data is not statistically significant. However, actual performance data does permit some interesting observations. For example, Figures* 6-4 and 6-5 depict availability data for Will County - Module A and the Green River System. The Will County System, which is the oldest of the six, has an average availability of 43.0 percent. This average represents rather erratic system performance and includes ten 1-month periods in which the system was not available at all. Green River, on the other hand, is the newest of the six systems. This system has an average availability of 82.6 percent which represents relatively stable system operation for the first year of operation.

These facts seem to suggest that the design and operation of FGD systems has benefited from experience gained over the past several years. This is a common stage in the development of most mechanical and chemical systems.

Another FGD system which has a high availability yet is relatively old is the LaCygne installation. Figure 6-6 illustrates the average reliability for the LaCygne scrubber. This average represents relatively stable system operation and no major failures (massive scaling, *etc.*). However, and important factor which the availability parameters masks is the maintenance manhours expended in servicing the system.

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*A complete set of graphs for other performance data is presented in Appendix C.

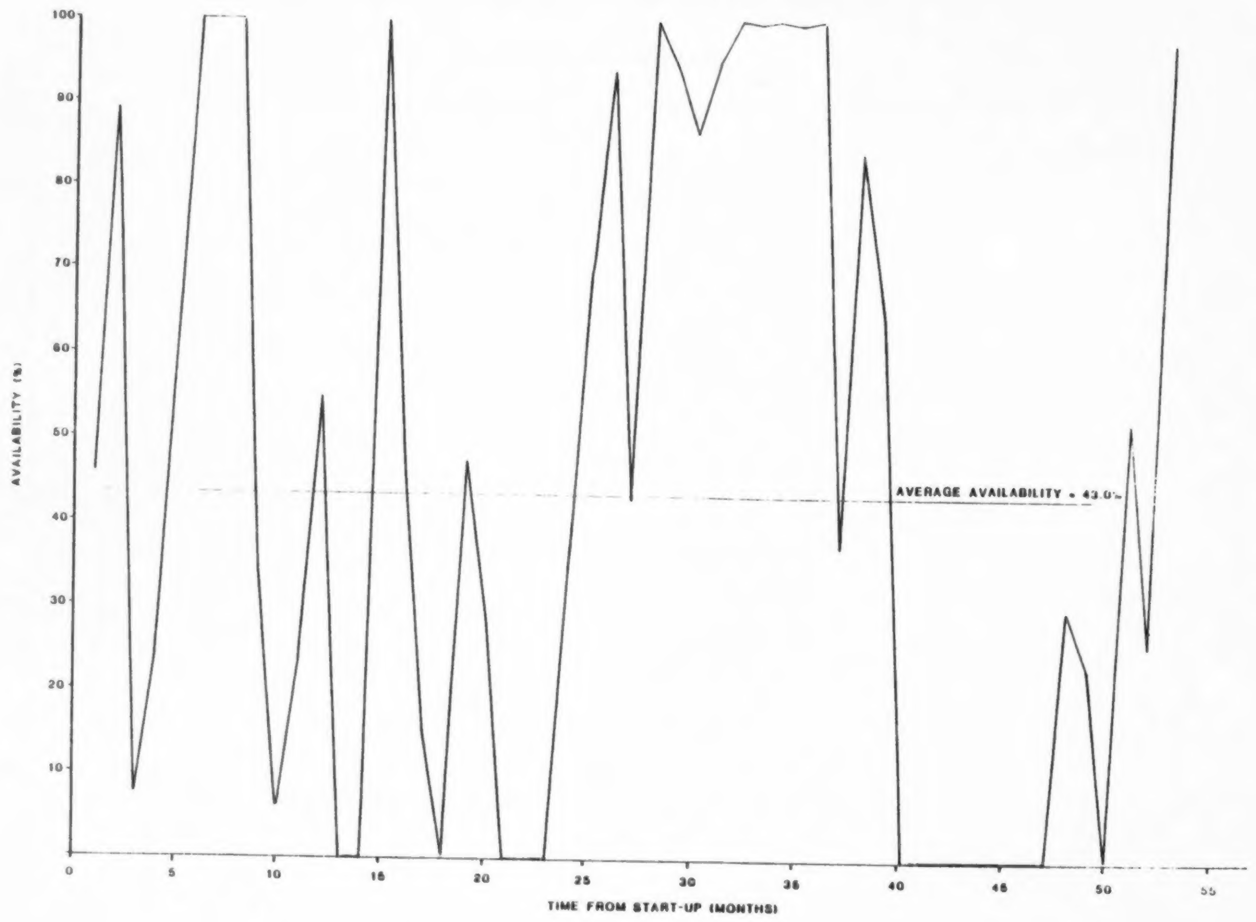

Figure 6-4. Will County FGD system availability - Module A.

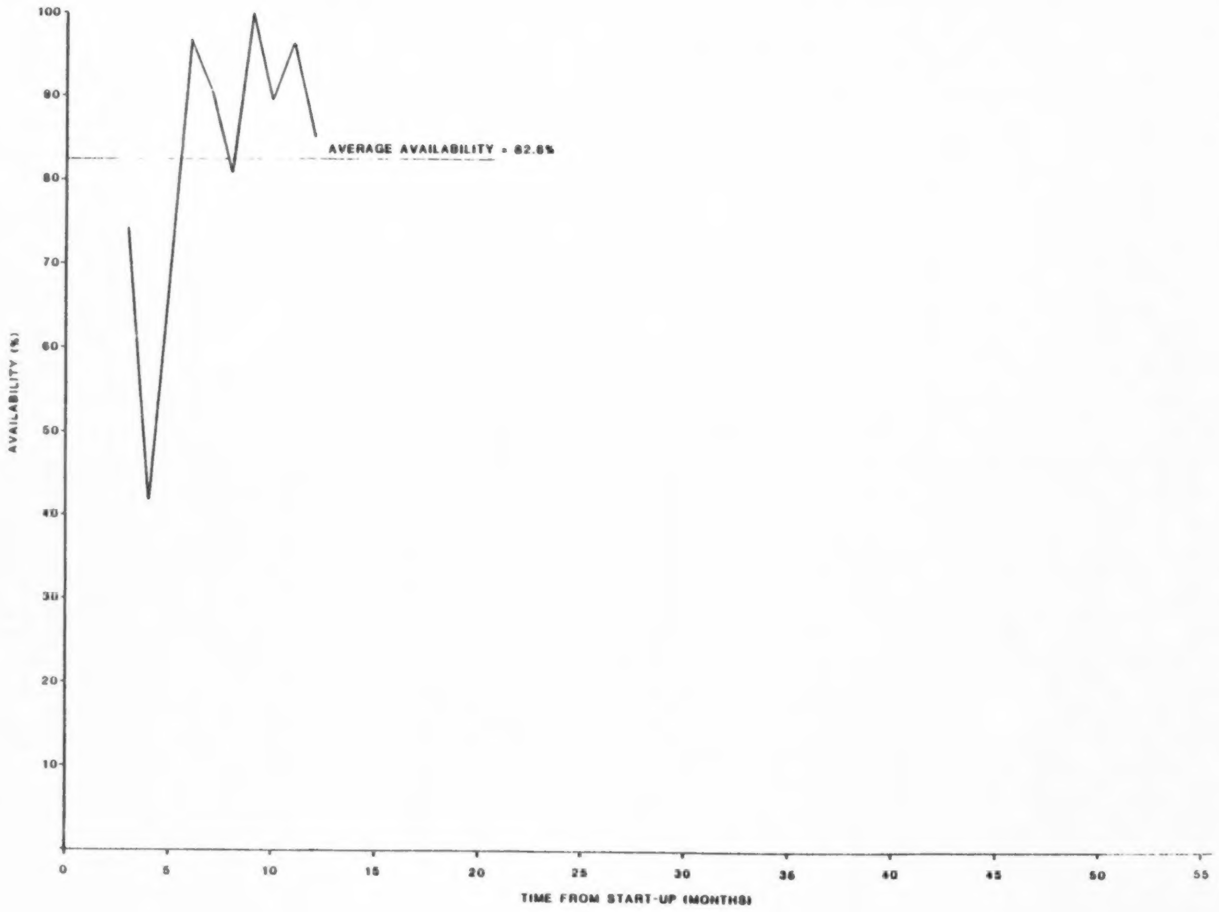

Figure 6-5. Green River FGD system availability.

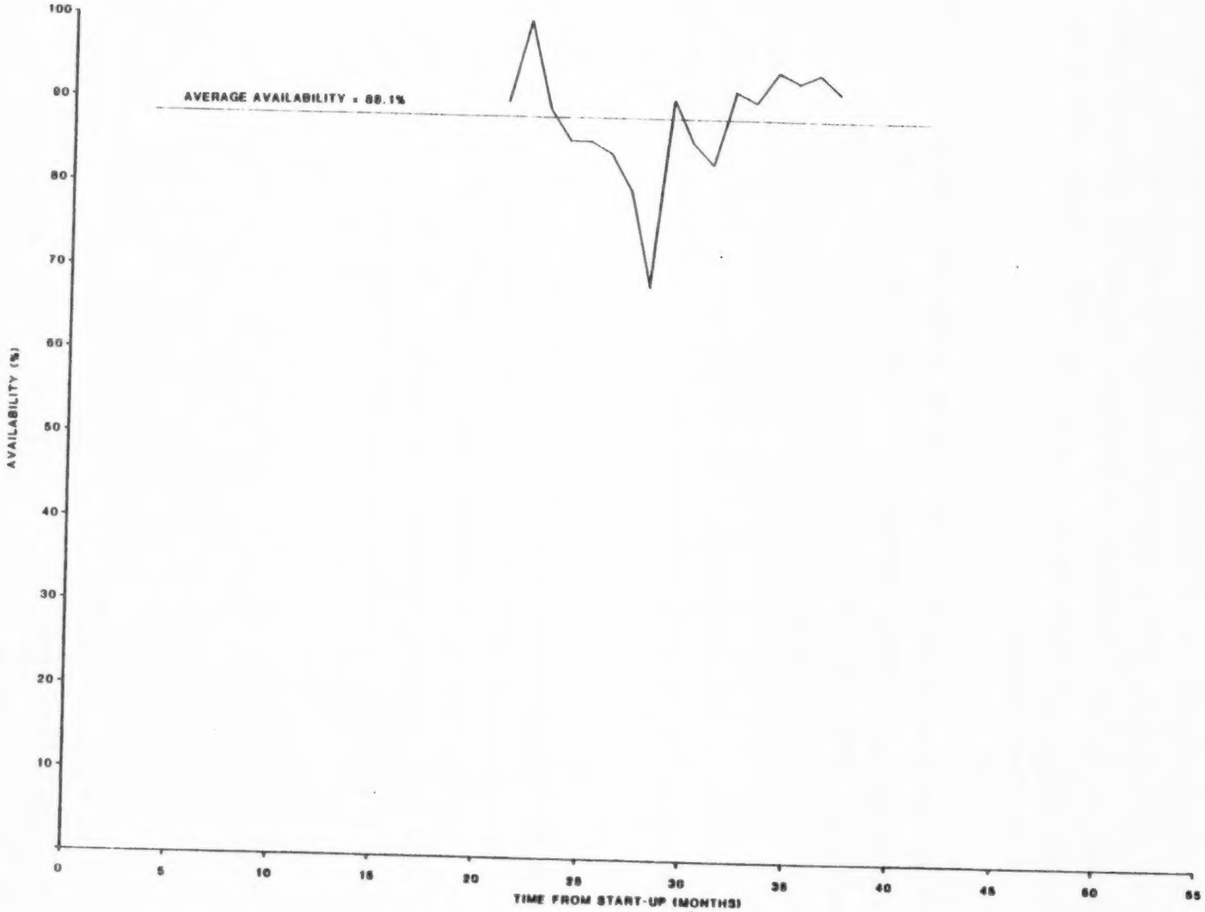

Figure 6-6. LaCygne FGD system availability - average all modules.

Current operating practice at the LaCygne scrubber is to shut one module down each night and have a maintenance crew clean and inspect the scrubber. The high system availability is in part attributable to the massive maintenance effort at LaCygne. The scrubber operating and maintenance force currently totals 51 people. Although the LaCygne system is a unique case, it does indicate that a scrubber can be operated reliably with sufficient expenditure of cost and effort.

Another interesting surmise can be made by observing Figure 6-7 which depicts reliability for Cholla - Module A. The Cholla system has a high average reliability (92.2 percent) along with several features which make Cholla unique among FGD systems. First, this system scrubs about 12 lbs SO_2 per ton of coal burned. This compares to other systems which scrub 72 to 180 lbs SO_2 per ton of coal burned. In addition, the Cholla system operates open loop with no water being recycled to the FGD system from the disposal pond.

The high average reliability of the Cholla FGD system can be attested to the above factors which serve to virtually eliminate the chemical scaling and plugging problems that have plagued many of the other FGD systems. The success of this unit seems to indicate that control of the process chemistry is of foremost importance in improving the reliability/availability of FGD systems.

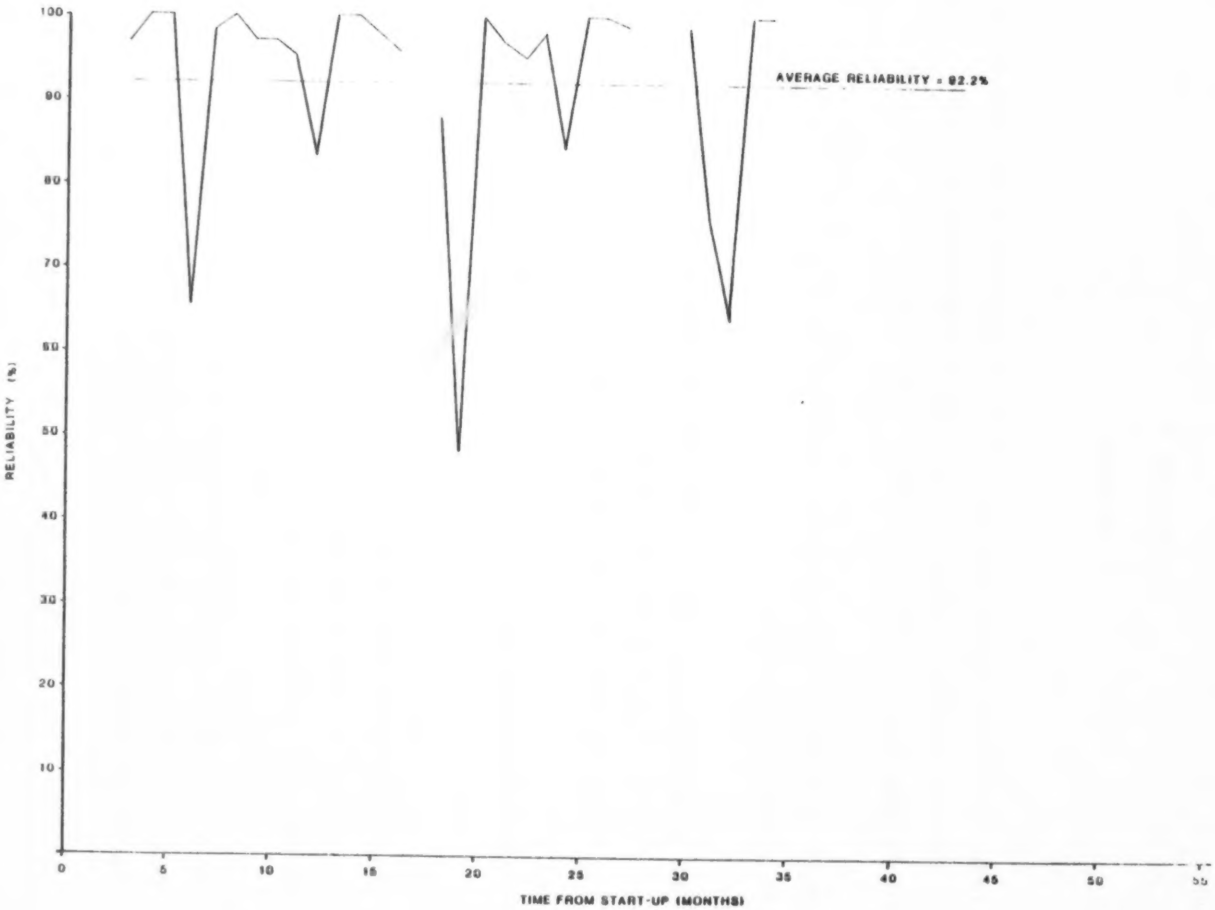

Figure 6-7. Cholla FGD system reliability - Module A.

SECTION 7

RESULTS

The results of this study indicate that several important operating parameters must be reported before a meaningful comparison of FGD systems and utility components can be made. In particular, for utility equipment:

1) Data to compute RMA should be reported to EEI on a mandatory basis.

2) The learning curve data in the EEI and FPC data banks should be examined and analyzed. This requires data reporting by unit and by age of unit.

The following information should be gathered for both existing and new FGD systems:

1) Data to compute RMA, mean time between failure, and mean time to repair should be reported to EEI as these data become available.

2) Mean time between full forced outages (MTBFFO) and mean time to repair full forced outages (MTTRFFO) should be reported to EEI.

Utilities are not required to submit data on RMA to EEI. Upon examining the EEI special data search, it was discovered that only a few utilities are currently reporting values for RMA. As a result, the RMA values reported by

EEI may not represent current practice. A concerted effort to gather the data necessary to complete RMA is required from a large number of utilities.

Learning curve data can be derived from a combination of the EEI data base and the Federal Power Commission (FPC) annual data reports required from each utility. The EEI data must, however, be available on a unit by unit basis to complete the combination. The current EEI procedures prohibit the dissemination of unit operating performance without the consent of the utility involved. This policy is under review by the Prime Movers Committee and may be revised.

The results of the search for FGD system performance data made it clear that current reporting procedures are both incomplete and inconsistent. All of the data required to calculate the Figure of Merit must be reported for FGD systems. Values for MTBFFO, MTTRFFO, RMA, and i (learning curve data) are not currently reported in any organized fashion. Certainly this is the major task which remains to be completed before any meaningful comparison can be made.

An important result of this study was the identification of the timeframe during which new FGD systems will be coming on line. Table 7-1 illustrates the estimated number of full scale (larger than 50 MW) lime/limestone systems which will have operated for at least one year in the years ending 1977 through 1980. Table 7-1 also projects confidence limits for predicting the availability of these systems during the same time span. An important assumption used to project these confidence limits is that data will be collected at all operating FGD systems as they come on line.

At this time, it is difficult to state with certainty exactly when a meaningful comparison of FGD systems and utility components can be made. Certainly, no comparison should be attempted before the performance of FGD

TABLE 7-1. PROJECTED CONFIDENCE LIMITS FOR AVAILABILITY PARAMETER - LIME/LIMESTONE SYSTEMS

Month/Year	Total Number of Lime/Limestone Systems with 1 Year of Operation[b]	Confidence Limit for Availability Parameter[a]	Confidence Level
12/77	16 (5,300 MW)	± 10.7%	90%
12/78	31 (13,000 MW)	± 7.4%	90%
12/79	41 (16,900 MW)	± 6.4%	90%
12/80	53 (22,700 MW)	± 5.6%	90%

---

[a] These confidence limits assume that availability is arrayed in a normal distribution about the average. In addition, it is assumed the standard deviation calculated in Section 6.3 is constant.

[b] These numbers are excerpted from PEDCo's FGD Summary Report (PE-227). The values for 1979 and 1980 are probably low due to the number of FGD systems which have not been selected.

systems can be estimated to ± 10.0 percent accuracy with 90 percent confidence. Table 7-1 indicates that at the earliest, this will be possible when data through the end of 1978 is available. This is, of course, contingent on acquiring accurate and meaningful data from both operational and new FGD systems.

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

Utility and FGD system performance data were collected and analyzed, and a comparison model was developed in an effort to compare the reliability/availability of FGD systems and utility equipment. The following conclusions and recommendations are presented to highlight the results of this study.

8.1 CONCLUSIONS

1) A statistically meaningful comparison of the reliability/availability of utility and FGD systems cannot now be made, primarily because of the small amount of FGD system performance data currently available. A meaningful comparison can be made after more FGD systems are installed and more complete performance records become available. Calculations show that FGD performance can be estimated to within 10 percent with a 90 percent confidence level when 1978 data becomes available if all FGD systems that are expected to come on line will report the necessary data.

2) The comparison model of Figure of Merit provides a better basis of comparing or ranking dissimilar pieces of equipment or systems than any single parameter currently being recorded. A meaningful comparison basis should include several parameters which effect the overall performance of a system or system component such as: 1) a measure of the maintenance/economic requirements, 2) a scale-up or learning

function, and 3) mechanical availability. The Figure of Merit developed in this study considers these factors which directly influence the performance of a piece of equipment to provide a valid basis for comparing dissimilar pieces of equipment or systems.

3) The product of Term I and Term II in the Figure of Merit exceeds 50 for all equipment installed by the utility industry. The boiler appears to be the equipment item within the utility industry which controls the unit performance. FGD systems will certainly have to demonstrate a performance such that the product of Term I and Term II is greater than 50 to demonstrate a performance characteristic which is comparable to the present components used in the utility industry.

8.2 RECOMMENDATIONS

1) The collection of complete performance data for both FGD and utility systems should be implemented on a regular basis. In particular, the terms identified in Section 4.2 of this report should be recorded. These are: mean time between full forced outage, mean time to repair a full forced outage, relative mechanical availability, and the number of replications of a piece of equipment or plant.

The cooperation of the utility industry should be enlisted in preparing a report similar to the Summary Report - Flue Gas Desulfurization Systems (PE-227) currently prepared by EPA. The set of parameters listed above should be reported for each FGD system so that meaningful comparisons can be made. This reporting procedure should include each new FGD system as it comes on line.

2) Any additional data collection efforts should be coordinated with either the ANSI steering committee on data availability or EEI in order to avoid burdening the utility industry with redundant data collection requests. Only one computer-based data collection system is required to accumulate and report the data on utility and FGD system. FEA, NARUC, NCR, EPRI, ANSI, FPC, CEQ, EEI, and EPA should identify their individual data requirements, then present one coordinated approach to the utility industry for obtaining the needed data.

3) Data concerning the "learning curve" or "number of replications" were not forthcoming from the search of the EEI data bank performed for this study. It is recommended that a special search to obtain this data from EEI be sponsored thru EEI.

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APPENDIX A

MODEL DEVELOPMENT

MODEL DEVELOPMENT

REQUIREMENTS FOR THE COMPARISON

The comparison technique should contain the following elements:

A) Existing data should be applicable to the comparison technique.

B) New data, if required, should not be too difficult to obtain.

C) The comparison technique should be relatively simple to compute and apply.

D) The comparison technique should include at least the following:

   1) "Mechanical" availability,
   2) Maintenance/economic measure, and
   3) Scale up or learning function.

MECHANICAL RELIABILITY

If a component within the utility unit or the unit itself is in the random failure state, then the reliability of the component or unit can be expressed as

$$R(t) = e^{-\lambda t} \quad ,$$

t = time of operation, and

λ = failure rate (occurrences per unit time).

Now define a similar term for the repair of a component or unit, again where repair is in the random repair state, such that

$$M(\tau) = e^{-\phi\tau} \quad ,$$

ϕ = repair rate (occurrences per unit time), and

τ = time of repair.

Thus, $M(\tau)$ is the probability that a repair will still be in progress after time, τ. Conversely, the probability that a repair will be complete within time τ is

$$M_c(\tau) = 1-e^{-\phi\tau} \quad ,$$

Now, take into account that satisfactory repair of the component is possible within the time constraint, τ, and that the component (or unit) would then be operational. The component may fail a second or third time, and on the occasion of each, a repair would be attempted. Based on the Poisson distribution, the probability a component will be operational at the end of time, t:

$$\begin{aligned}
\text{without a failure} &= e^{-\lambda t} \\
\text{with one failure} &= \lambda t e^{-\lambda t} \\
\text{with two failures} &= \frac{(\lambda t)^2 e^{-\lambda t}}{2} \\
&\vdots \\
\text{with i failures} &= \frac{(\lambda t)^i e^{-\lambda t}}{i!}
\end{aligned}$$

Now, following every failure, a repair is attempted. The probability that the repair will be completed in time, τ, is $(1-e^{-\phi\tau})$. The probability of a component with one failure being repaired within τ and being operational at the end of time t, is

$$\lambda t e^{-\lambda t}(1-e^{-\phi\tau}) \quad .$$

Similarly, with i failures, the probability of each failure being repaired in time, τ, and the unit being operational at the end of time, t, is

$$\frac{(\lambda t)^i e^{-\lambda t}}{i!}(1-e^{-\phi\tau})^i \quad .$$

The probability of repairing all failures within the time, τ, and being operational at the end of time, t, is

$$\sum_{i=0}^{\infty} \frac{(\lambda t)^i e^{-\lambda t}(1-e^{-\phi\tau})^i}{i!}$$

$$e^{-\lambda t} \sum_{i=0}^{\infty} \frac{(\lambda t)^i (1-e^{-\phi\tau})^i}{i!}$$

$$(e^{-\lambda t}) \left[e^{\lambda t(1-e^{-\phi\tau})} \right]$$

$$e^{-\lambda t e^{-\phi\tau}} \quad . \qquad [1]$$

This equation defines reliability such that if a unit or component is repaired within a time, τ, and is operational at the end of time, t, the unit or component has successfully performed its task.

Discussion

In practice the failure rate, λ, is the reciprocal of the mean time between failures. The repair rate, ϕ, is the reciprocal of the mean time to repair. Both of these terms apply only in the random failure or repair modes when the rates are constant with respect to time and do not include early or premature failure modes or wear out failure modes.

This approach toward reliability then gives almost equal credit to the component which has 1) an extremely long time between failures and associated long time to repair, and 2) frequent failures and short repair times. An analogy might be that 1) is an extremely thoroughly designed and quality-built component versus 2) which is produced without benefit of all of the effort associated with (1). This represents the trade-off between initial capital investment and continuing maintenance expense. Equation [1] addresses requirement item D(1).

RELATIVE MECHANICAL AVAILABILITY (RMA), A MEASURE OF EFFORT

"Relative Mechanical Availability is a form of Operating Availability adjusted to show relative effort. The prime assumption is that most outage time is affected by work schedules and crew sizes. Relative Mechanical Availability uses an Adjusted Outage Time (AOT) based on effort. Manhours worked is a measure of effort which is reasonably independent of work schedules and crew sizes. Manhours worked (MH) divided by a standard work force (SWF) gives a derived time worked based on effort. If we assume a round-the-clock schedule, then this derived time worked is almost a derived outage time based on effort. The difference is the amount of outage time which is independent of effort called Hours Waiting (HW)."[1]

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[1] The quotations are from EEI publication 75-50, "Report on Equipment Availability for the Ten-Year Period 1965-1974, (ED-058).

Hours waiting is "that portion of time for any outage during which no work could be performed. This includes time for cooling down equipment and shipment of parts. This is time that could not be affected by a change in work schedule or the number of men worked."

An arbitrary assumption of ten men for the standard work force gives:

$$AOT = HW + MH/10 \quad .$$

Then, substituting AOT for outage time in the equation for operating availability gives:

$$\begin{aligned} RMA &= [(PH-AOT)/PH]\ 100 \\ & [(PH-(HW + MH/10))/PH]\ 100 \end{aligned}$$

Where

PH, the Period Hours, is "the clock hours in the period under consideration. (Generally one year)."

Discussion

RMA is a factor which directly considers the repair effort required to return equipment to an "available" status. It is possible that RMA could be negative if the manhours for repair are ten times greater than the total period hours (excluding waiting time considerations). This would indicate an extremely labor intensive component. RMA then is a maintenance/economic measure as stated in requirement D(2).

THE LEARNING FUNCTION

The learning function is a measure of increased performance based on repetition. In design and manufacturing, the learning function can be handled as decreasing alloted time for a given function or as a single time allotment with a decreasing learning factor. Each of these approaches is applied to a measurable function and tends to decrease the alloted time for a given function as the number of repetitions is increased. This function nominally takes the form shown in Figure A-1.

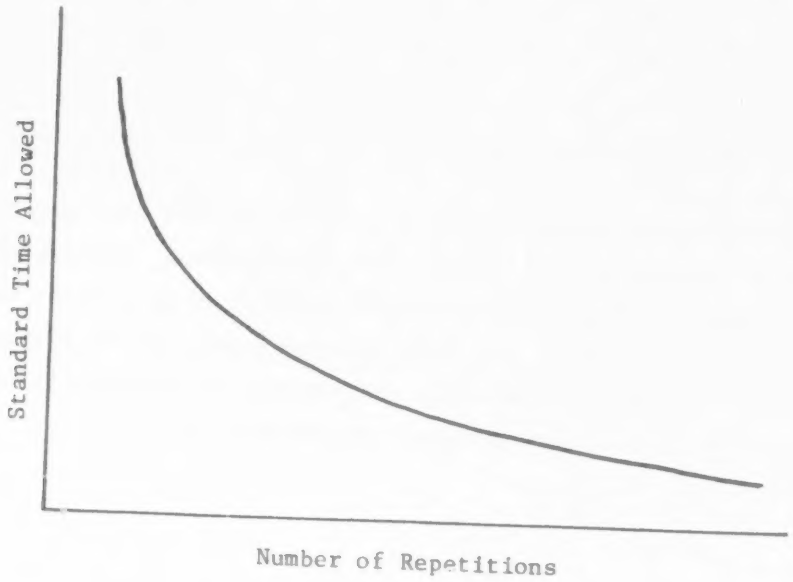

Figure A-1. Learning curve showing decrease of standard time with increase of repetitions.

The analogy in central station design, construction and operation is increased performance with decreased cost as a function of the number of repetitions completed. In this case, the time span to complete a learning cycle is much longer than ever encountered in manufacturing operations.

For purposes of this comparison model, the learning function is a simple fraction raised to an exponent. This form is suggested by the similarity between the classical learning function curve (MA-875) and the "six-tenths" factor curve (PE-030). The six-tenths factor applied to the learning function has values as shown in Table A-1.

TABLE A-1. VALUES OF THE LEARNING FUNCTION

i	$\left(\frac{i}{i+1.0}\right)^{0.6}$	$\left(\frac{i}{i+1.0}\right)^{-0.6}$
1	.66	1.52
2	.78	1.27
3	.84	1.19
4	.87	1.14
5	.90	1.11

Based on this learning function, a potential 25 percent increase in the Figure of Merit can be achieved after five repetitions. The learning function in the Figure of Merit computation is applied in an inverse manner. The Figure of Merit for the first of a kind component can be compared with a component which has had the benefit of repetition on essentially an equal basis. The learning function addresses requirement D(3).

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APPENDIX B
UTILITY COMPONENT DATA

The data presented in Appendix B were obtained from operating utilities for several different types and sizes of boilers and turbines. Each data point on a figure represents the average availability for one component year of service, starting at year zero when the component was declared commercially available. The heavy line in each figure connects the average availability for all components during the year of service.

Note: The definition of availability for all figures in Appendix B is the hours a unit is synchronized to the bus divided by the period hours. This definition yields availabilities lower than would be computed using the EEI definition. The difference is in the time necessary to bring a unit up to synchronic speed and bus connection. This can amount to as much as 36 hours difference per start for large units.

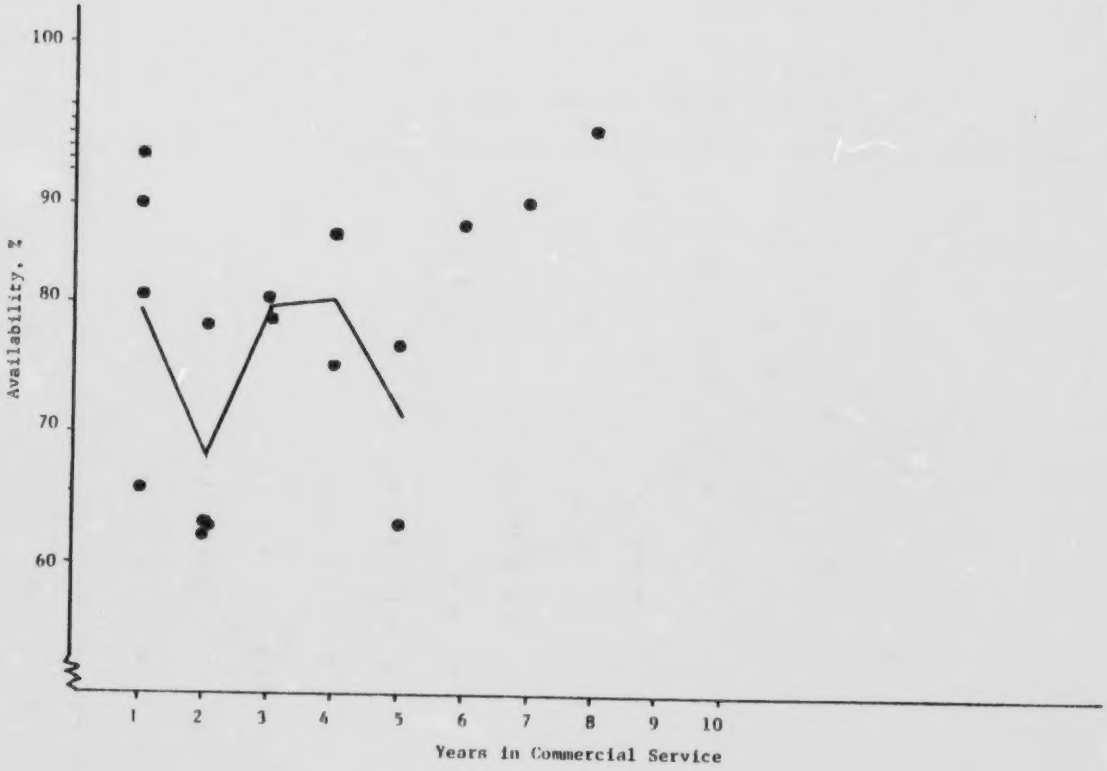

Figure B-1. Super critical, once thru boilers availability *vs*. years in service.

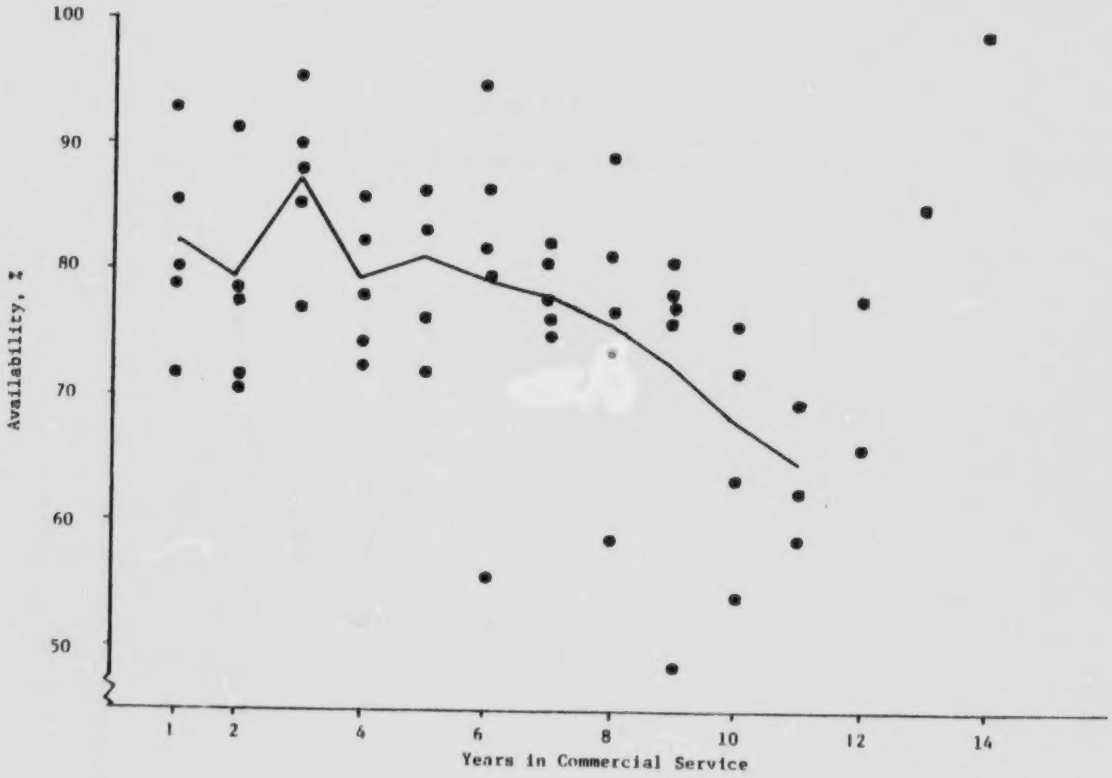

Figure B-2. Boiler, larger than 500 MW availability *vs*. years in service.

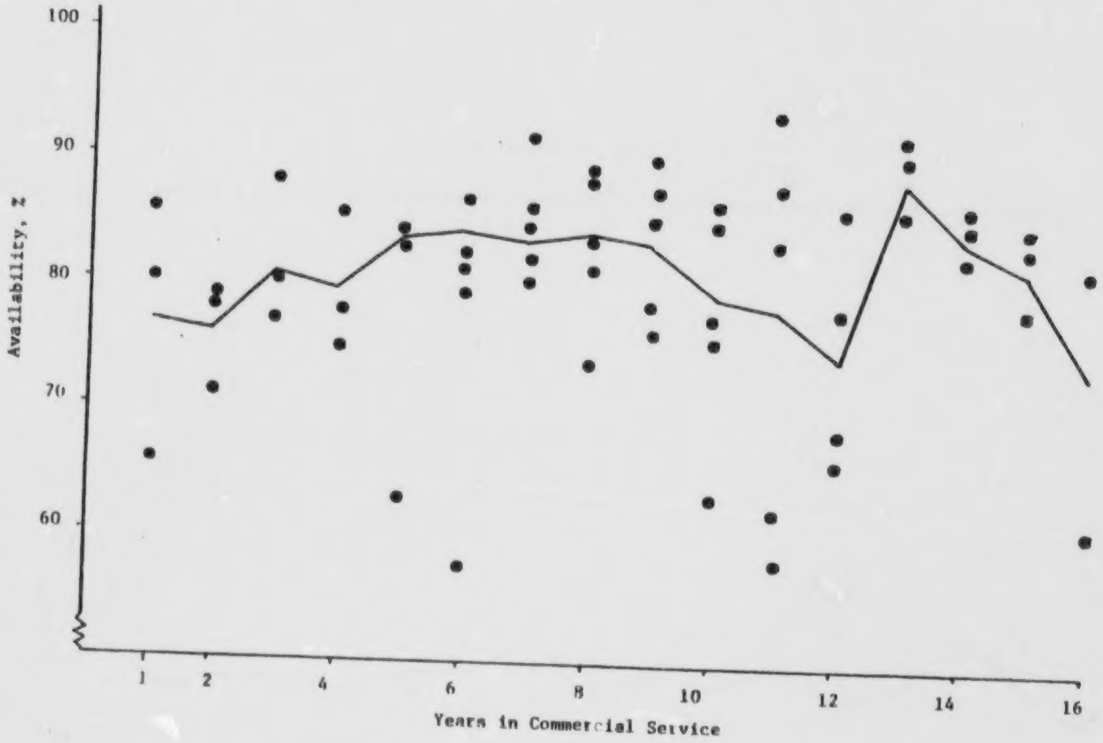

Figure B-3. Boiler, 300 MW availability *vs.* years in service.

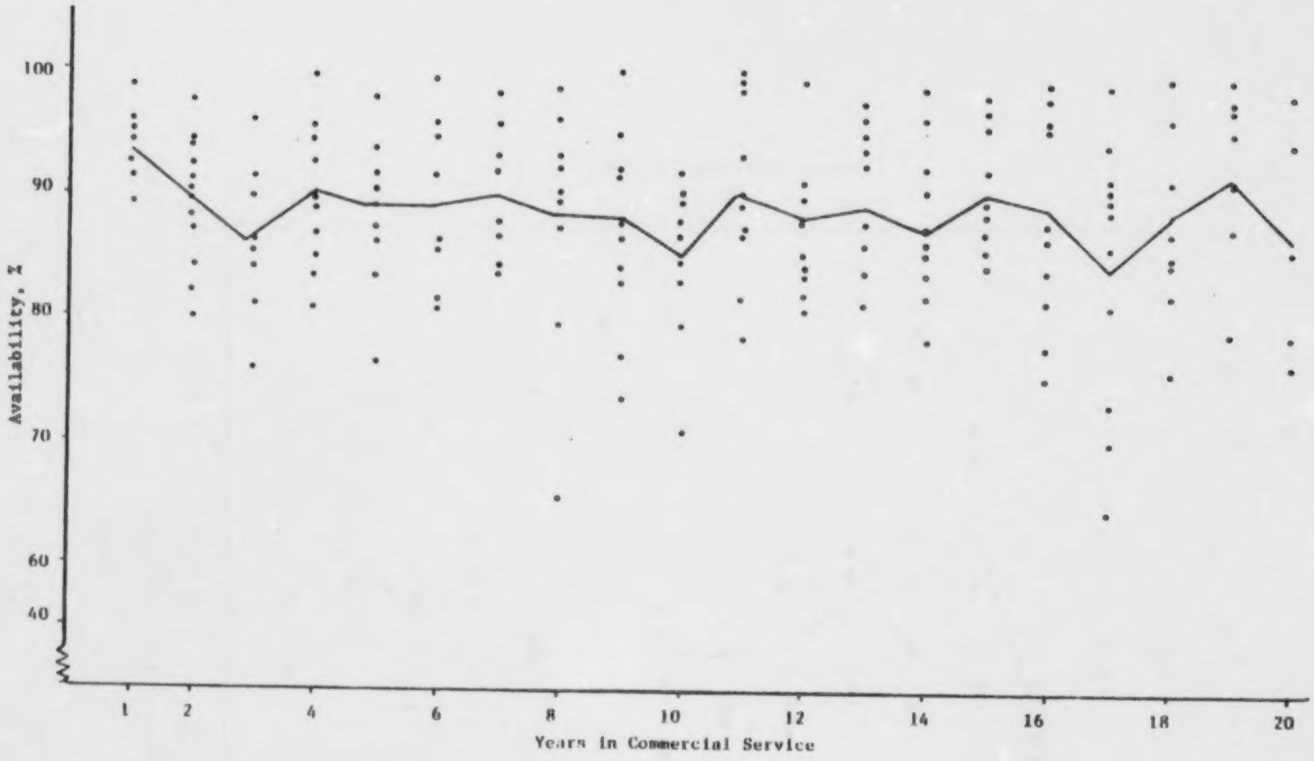

Figure B-4. Boiler, 200 MW size availability *vs*. years in service.

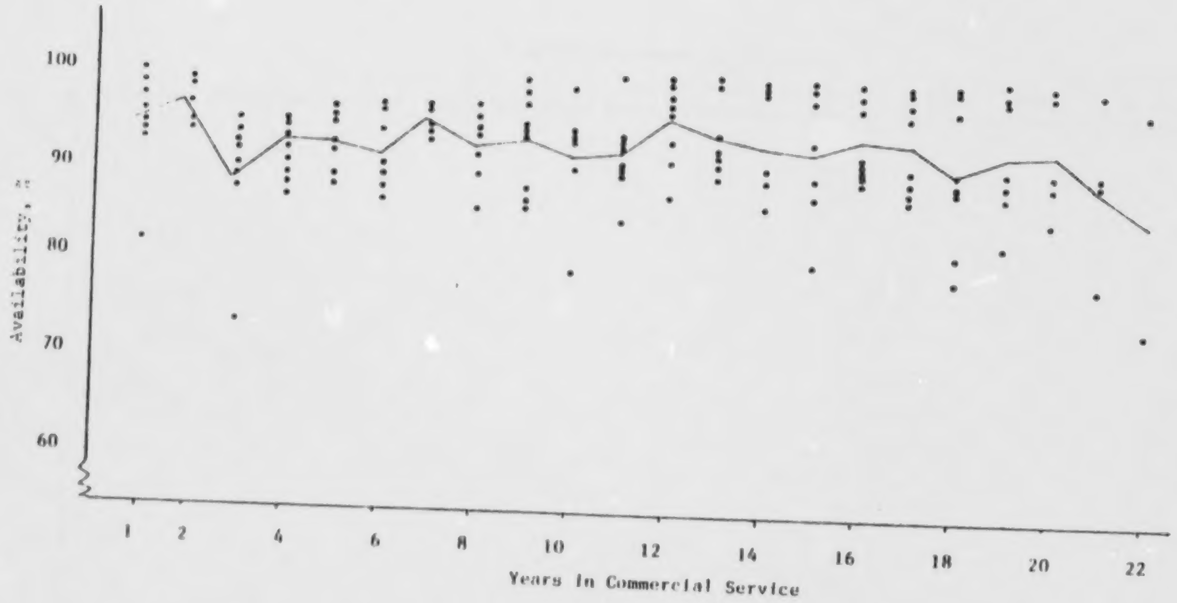

Figure B-5. Boiler, 175 MW size availability *vs.* years in service.

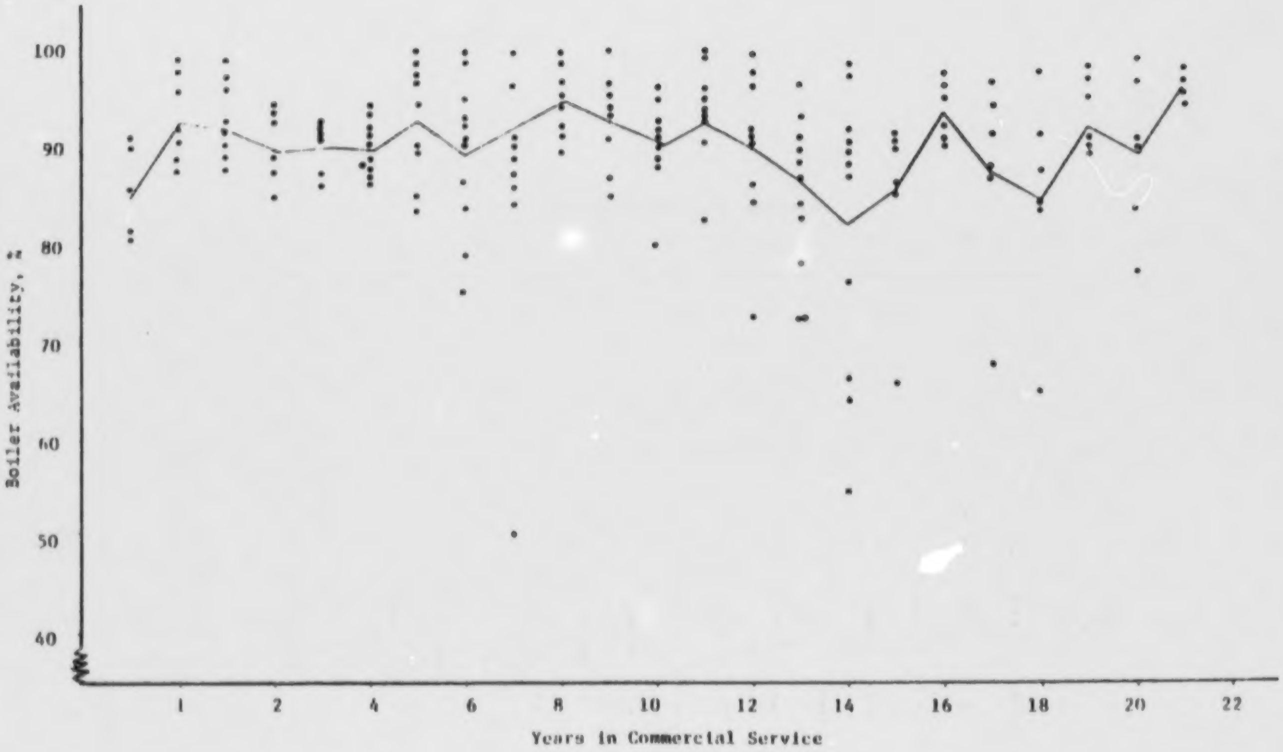

Figure B-6. Boiler, 125-150 MW size availability *vs.* years in service.

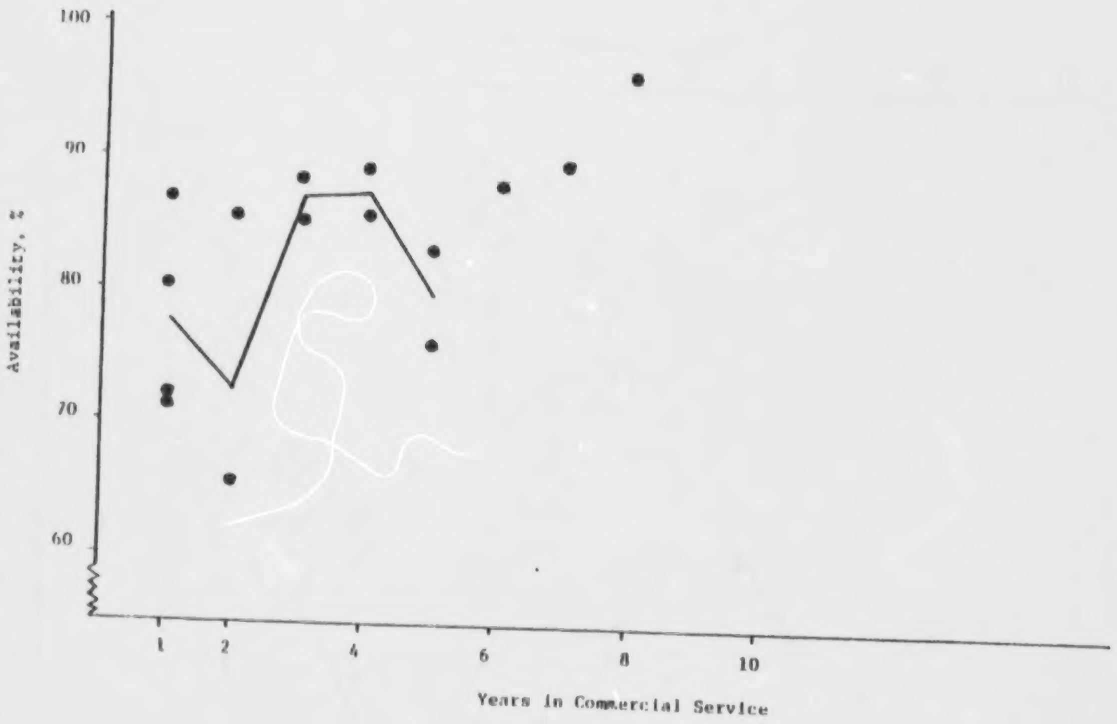

Figure B-7. Steam turbine, >500 MW size, super critical availability *vs*. years in service.

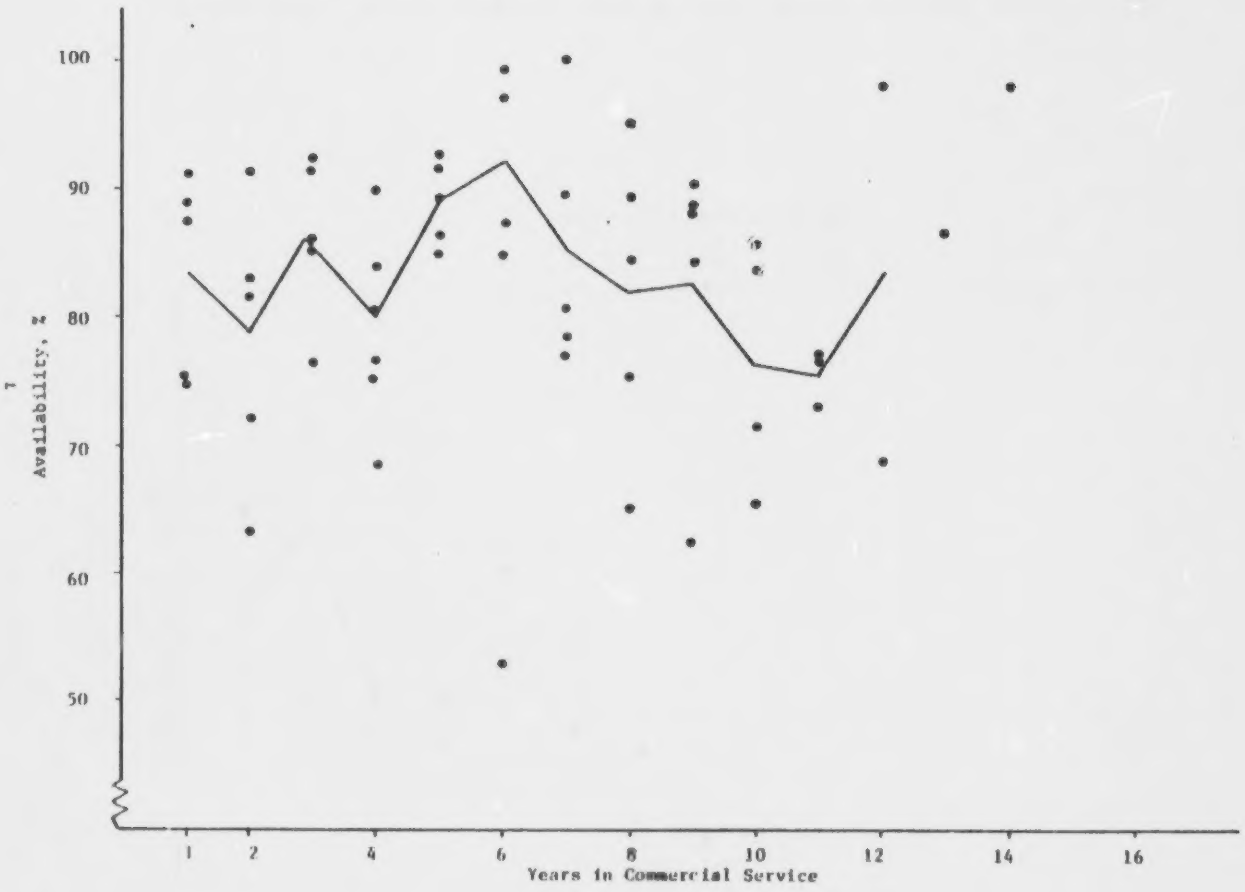

Figure B-8. Steam turbine, 300-500 MW size, availability *vs*. years in service.

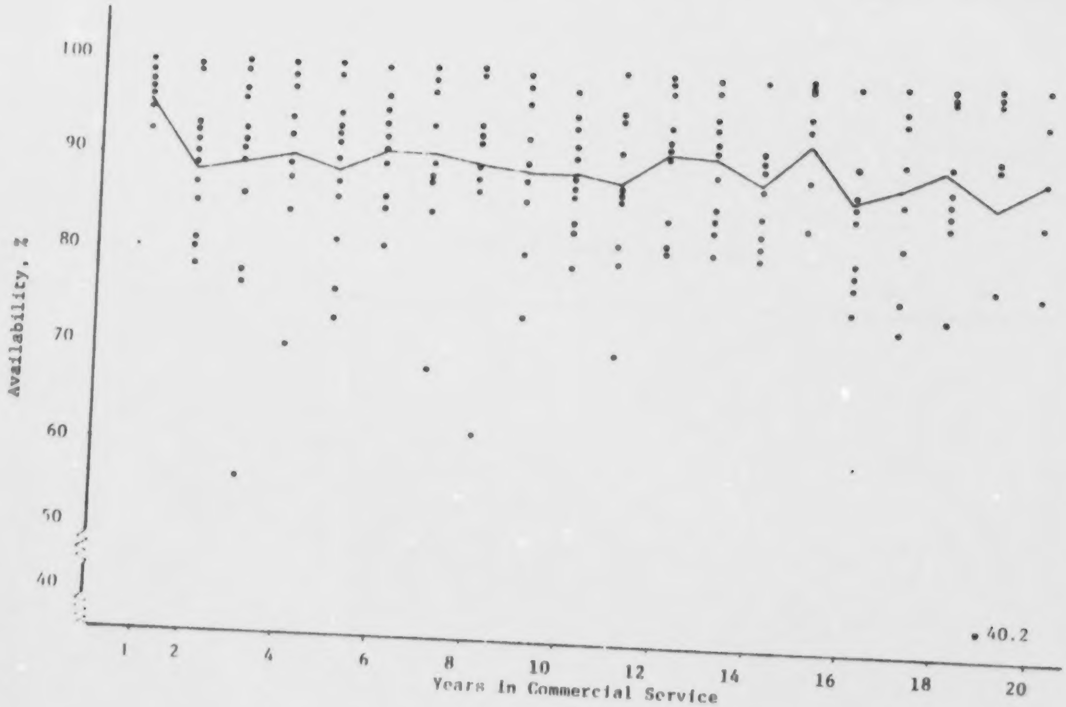

Figure B-9. Steam turbine, 200 MW size availability *vs.* years in service.

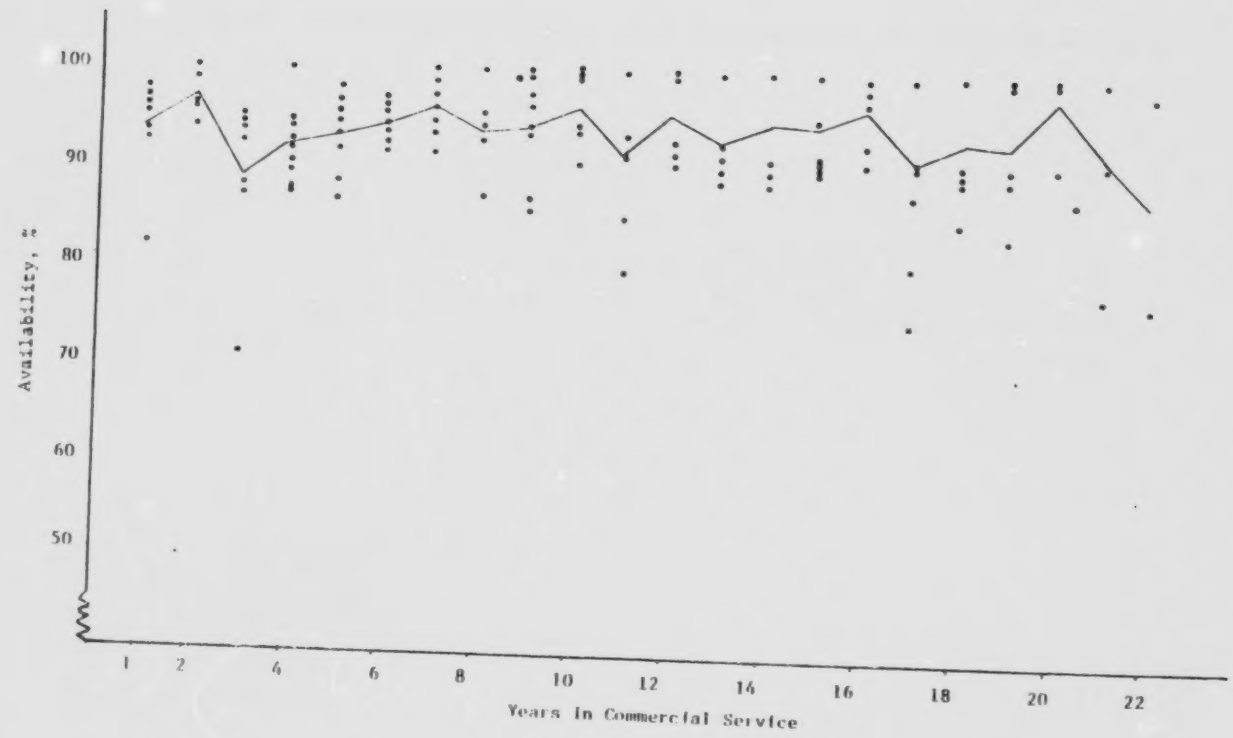

Figure B-10. Steam turbine, 175 MW size availability *vs.* years in service.

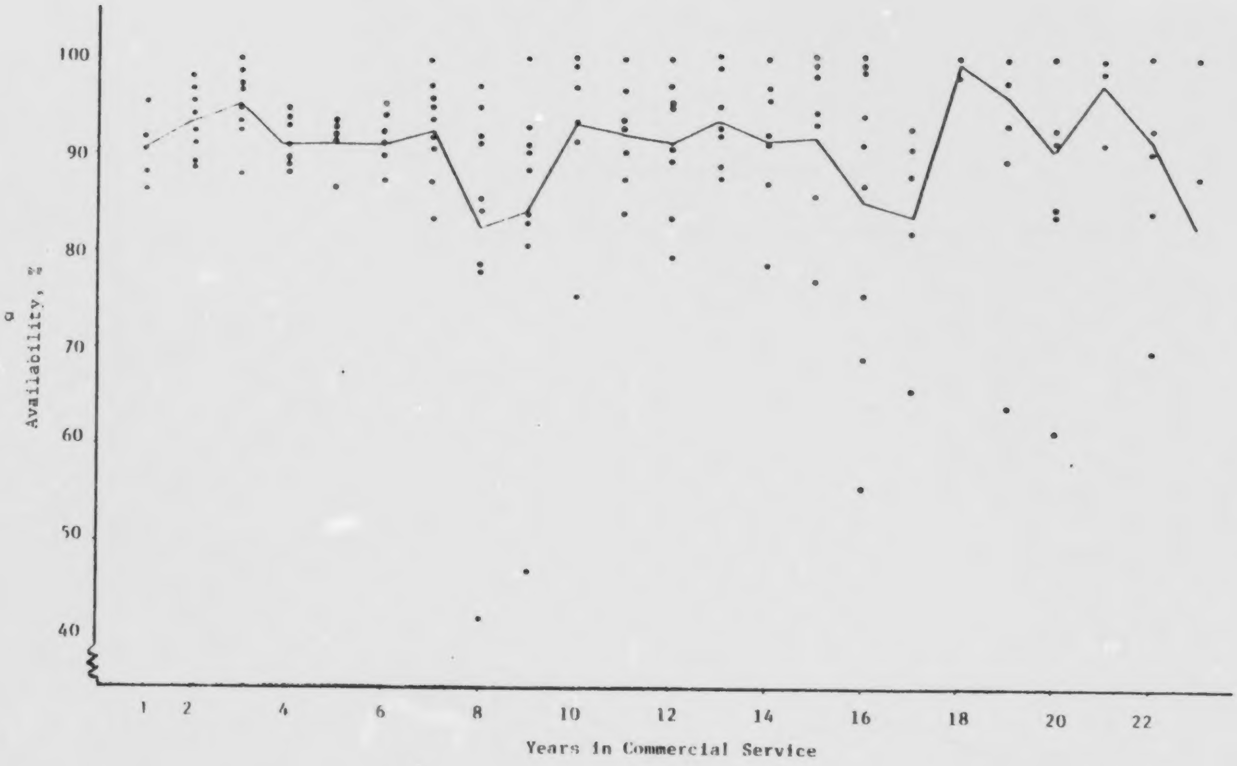

Figure B-11. Steam turbine, 125-150 MW size availability *vs.* years in service.

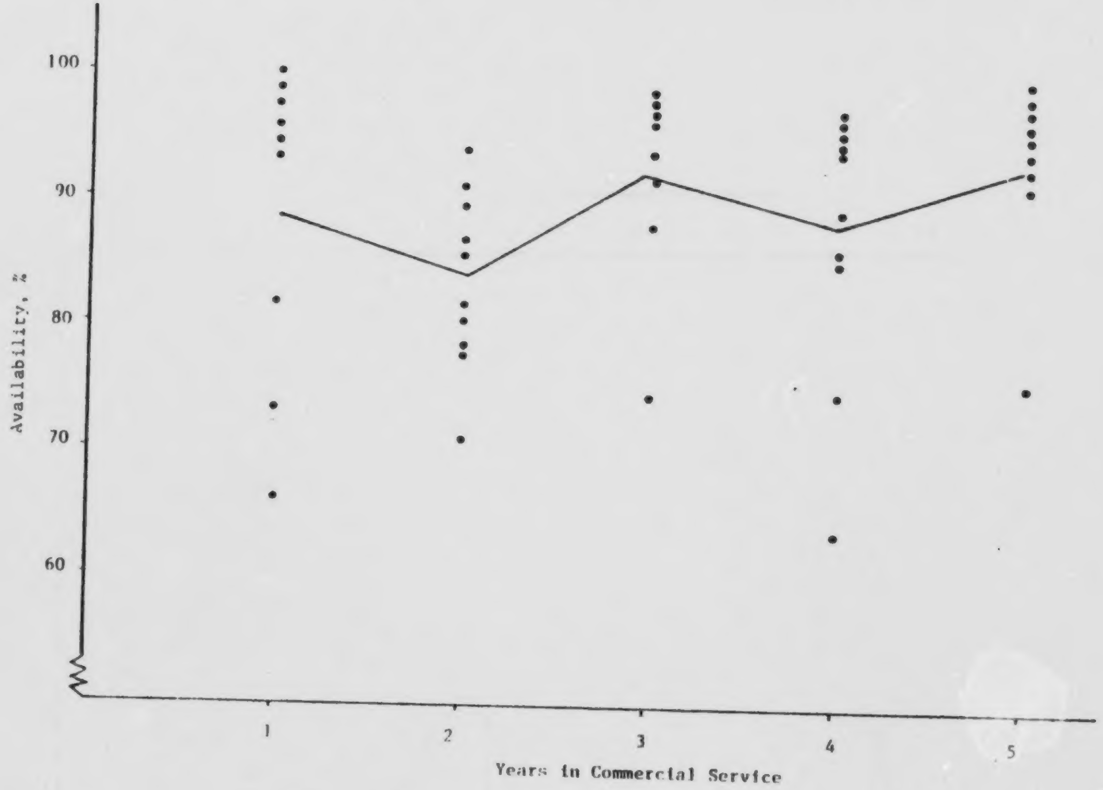

Figure B-12. Gas turbine, 20-25 MW size availability *vs*. years in service.

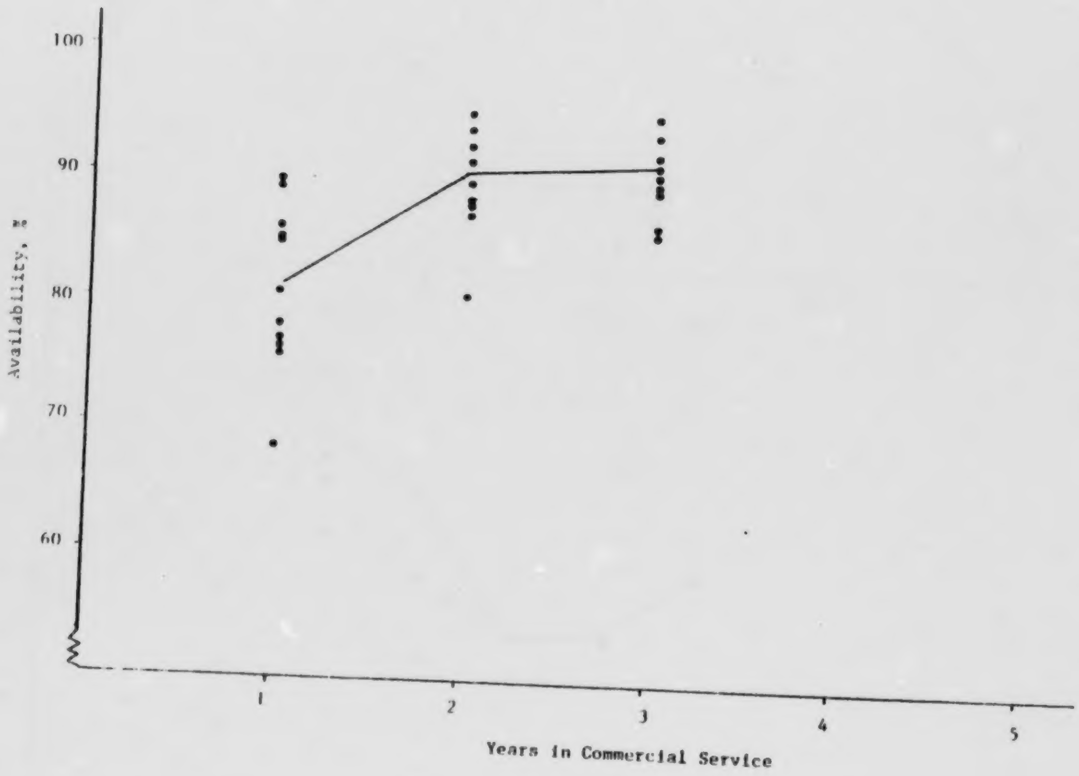

Figure B-13. Gas turbine, 59-70 MW size availability *vs.* years in service.

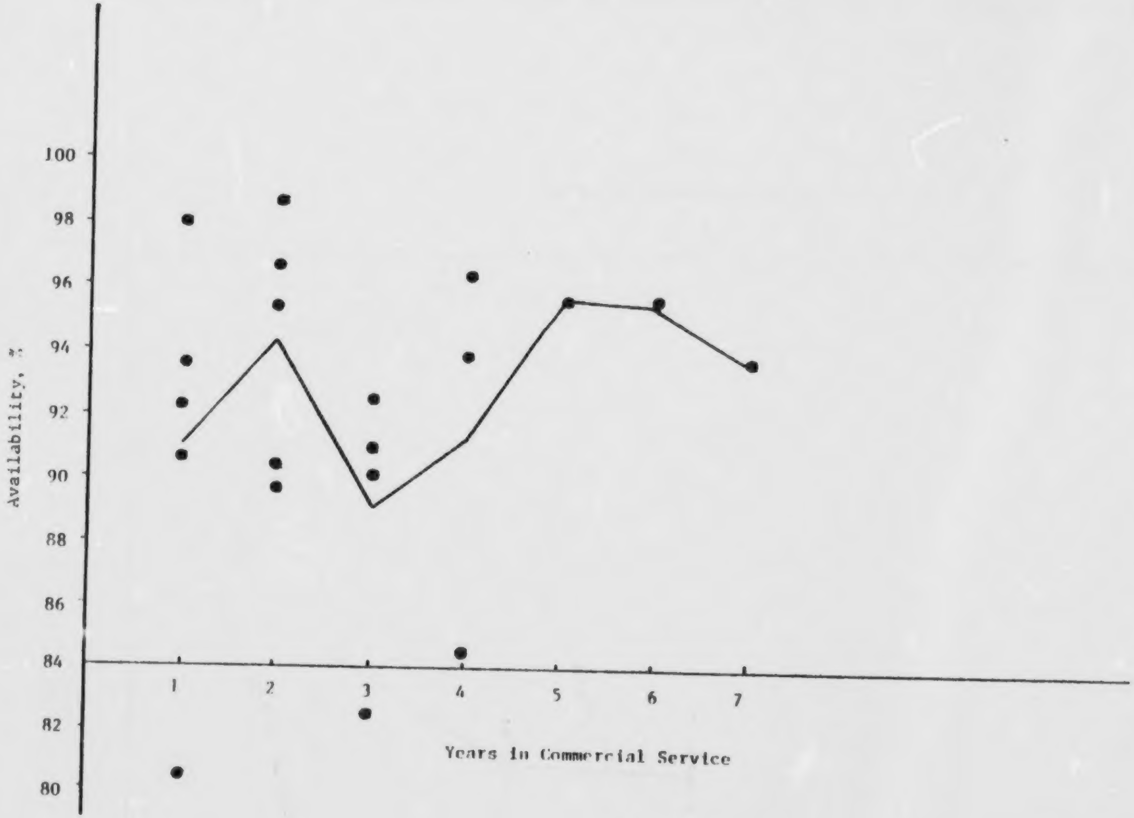

Figure B-14. Electrostatic precipitators availability *vs.* years in service.

APPENDIX C
FGD SYSTEM DATA

The information presented in Appendix C is divided into three basic areas:

1) FGD System Reliability Information
2) Graphical Representations of FGD System Performance
3) Calculations

The data presented in the first section are the monthly performance statistics for the following FGD systems.

1) Arizona Public Service Company's Cholla Generating Station - Unit No. 1.

2) Commonwealth Edison Company's Will County Station - Unit No. 1.

3) Duquesne Light Company's Phillips Station.

4) Kansas City Power and Light Company's LaCygne Station.

5) Kentucky Utilities Company's Green River Station.

6) Louisville Gas and Electric Company's Paddy's Run Station - Unit No 6.

Most of the data presented are on an hours per month basis. However, in some instances this information was not forthcoming and the values for certain performance parameters are expressed on a percentage basis.

The data in this first section are limited to the "FGD Reliability Information" Forms 1 and 2. Radian was not able to complete Form 3 for any system and Forms 1 and 2 have only been partially completed.

The second section of this Appendix contains a series of figures. These figures are a graphical representation of the data presented in Form 2. The figures represent month by month performance of the FGD system. The average value of the system performance is also illustrated in these figures.

The final section of this Appendix contains detailed calculations which were used to determine the ranges for the four FGD system performance parameters. These ranges are presented in Table 6-5 in the body of the report.

FGD SYSTEM RELIABILITY INFORMATION
FORMS 1 AND 3

Form #1

FGD SYSTEM RELIABILITY INFORMATION

System	Cholla
Start-Up Date	10/73
Number of Modules	2
Size of Modules (ACFM)	260,000
Total System Operating Hours	
Total Boiler Hours in Period for which Data is Available	
Total Hours System was Required to Operate	
Total Hours System was Available to Operate	
Longest Continuous System Operation	
Average Load on System per Operating Hour	
Maintenance Hours per Module per Week	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Cholla MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Reliability (%)	Hours Module Was Available to Operate
1/74				97	
2/74				100	
3/74				100	
4/74				66	
5/74				98	
6/74				100	
7/74				97	
8/74				97	
9/74				95	
10/74				83	
11/74				100	
12/74				100	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Cholla MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Reliability (%)	Hours Module Was Available to Operate
1/75				98	
2/75				96	
3/75					
4/75				88	
5/75				48	
6/75				100	
7/75				97	
8/75				95	
9/75				98	
10/75				84	
11/75				100	
12/75				100	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Cholla MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Reliability (%)	Hours Module Was Available to Operate
1/76				99	
2/76					
3/76					
4/76				99	
5/76				76	
6/76				64	
7/76				100	
8/76				100	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Cholla MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Reliability (%)	Hours Module Was Available to Operate
1/74				90	
2/74				94	
3/74				66	
4/74				57	
5/74				99	
6/74				100	
7/74				92	
8/74				97	
9/74				99	
10/74				68	
11/74				98	
12/74				100	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Cholla MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Reliability (%)	Hours Module Was Available to Operate
1/75				99	
2/75				99	
3/75					
4/75				65	
5/75				40	
6/75				100	
7/75				98	
8/75				100	
9/75				97	
10/75				55	
11/75				80	
12/75				100	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Cholla MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Reliability (%)	Hours Module Was Available to Operate
1/76				99	
2/76					
3/76					
4/76				98	
5/76				100	
6/76				39	
7/76				98	
8/76				100	

Form #1

FGD SYSTEM RELIABILITY INFORMATION

System	Will County
Start-Up Date	2/72
Number of Modules	2
Size of Modules (ACFM)	385,000
Total System Operating Hours	A=12681 B=6458
Total Boiler Hours in Period for which Data is Available	29234
Total Hours System was Required to Operate	
Total Hours System was Available to Operate	A=17754 B=9435
Longest Continuous System [illegible]ation	
Average Load on System per Operating Hour	
Maintenance Hours per Module per Week	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Will County MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/72		Not Available	0		
2/72			0		
3/72	628		0		0
4/72	640		218		333
5/72	525		365		667
6/72	649		55		55
7/72	649		179		179
8/72	690		476		476
9/72	46		0		720
10/72	0		0		744
11/72	226		0		720
12/72	719		150		253

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Will County MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/73	568	Not Available	48		48
2/73	672		161		161
3/73	656		413		413
4/73	614		0		0
5/73	735		0		0
6/73	512		107		720
7/73	677		324		360
8/73	668		110		110
9/73	553		6		6
10/73	738		355		355
11/73	633		201		201
12/73	627		0		0

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Will County MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74	744	Not Available	0		0
2/74	647		0		0
3/74	426		110		278
4/74	684		495		502
5/74	744		693		697
6/74	553		302		307
7/74	706		676		744
8/74	659		601		705
9/74	647		549		624
10/74	738		691		703
11/74	632		613		720
12/74	744		738		741

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Will County MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75	685	Not Available	676		744
2/75	666		662		667
3/75	609		604		743
4/75	638		252		267
5/75	744		628		628
6/75	642		389		462
7/75	689		0		0
8/75	565		0		0
9/75	720		0		0
10/75	194		0		0
11/75	0		0		0
12/75	0		0		0

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Will County MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76	0	Not Available	0		0
2/76	0		0		0
3/76	309		140	309	224
4/76	692		138	692	166
5/76	665		0	665	0
6/76	612		271	612	374
7/76	588		0	588	192
8/76	495		285	495	731

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Will County MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/72		Not Available			
2/72	121		47		55
3/72	628		247		247
4/72	640		88		88
5/72	525		167		167
6/72	649		201		201
7/72	649		117		117
8/72	690		146		146
9/72	46		18		720
10/72	0		0		744
11/72	226		37		720
12/72	719		170		273

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Will County MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/73	568	Not Available	64		64
2/73	672		110		110
3/73	656		70		70
4/73	614		84		84
5/73	735		0		
6/73	512		0		
7/73	677		0		
8/73	668		0		
9/73	553		0		
10/73	738		0		
11/73	633		0		
12/73	627		0		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Will County MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74	744	Not Available	0		
2/74	647		0		
3/74	426		0		
4/74	684		0		
5/74	744		0		
6/74	553		0		
7/74	706		0		
8/74	659		0		
9/74	647		0		
10/74	738		0		
11/74	632		0		
12/74	744		0		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Will County MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75	685	Not Available	0		
2/75	666		0		
3/75	609		0		
4/75	638		0		
5/75	744		276		276
6/75	642		543		616
7/75	689		547		589
8/75	565		565		696
9/75	720		452		452
10/75	194		194		194
11/75	0		0		0
12/75	0		0		0

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Will County MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76	0	Not Available	0		0
2/76	0		0		0
3/76	309		63		65
4/76	692		340		368
5/76	665		567		644
6/76	612		517		621
7/76	588		524		599
8/76	495		304		487

Form #1

FGD SYSTEM RELIABILITY INFORMATION

System	Phillips
Start-Up Date	7/73
Number of Modules	4
Size of Modules (ACFM)	400,000
Total System Operating Hours	
Total Boiler Hours in Period for which Data is Available	
Total Hours System was Required to Operate	
Total Hours System was Available to Operate	
Longest Continuous System Operation	
Average Load on System per Operating Hour	
Maintenance Hours per Module per Week	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Phillips MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75					
2/75					
3/75					
4/75					
5/75					
6/75					
7/75			400		
8/75			478		
9/75			57		
10/75			607		
11/75			626		
12/75			360		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Phillips MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76			277		
2/76			657		
3/76			695		
4/76					
5/76					
6/76					
7/76					
8/76					

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Phillips MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75					
2/75					
3/75					
4/75					
5/75					
6/75					
7/75			180		
8/75			682		
9/75			561		
10/75			207		
11/75			720		
12/75			661		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Phillips MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76			536		
2/76			662		
3/76			353		
4/76					
5/76					
6/76					
7/76					
8/76					

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Phillips MODULE C

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75					
2/75					
3/75					
4/75					
5/75					
6/75					
7/75			537		
8/75			323		
9/75			685		
10/75			505		
11/75			0		
12/75			182		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Phillips MODULE C

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76			101		
2/76			166		
3/76			659		
4/76					
5/76					
6/76					
7/76					
8/76					

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Phillips MODULE D (two-stage)

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75					
2/75					
3/75					
4/75					
5/75					
6/75					
7/75			723		
8/75			319		
9/75			536		
10/75			487		
11/75			75		
12/75			386		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Phillips MODULE D

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76			707		
2/76			406		
3/76			401		
4/76					
5/76					
6/76					
7/76					
8/76					

Form #4

FGD SYSTEM RELIABILITY INFORMATION

System Phillips Module A,B,C,&D

	Hours Boiler Operated					
Month/ Year	Boiler #1	Boiler #2	Boiler #3	Boiler #4	Boiler #5	Boiler #6
1/75						
2/75						
3/75						
4/75						
5/75						
6/75						
7/75	83	644	703	349	605	643
8/75	354	701	454	457	517	445
9/75	463	287	669	503	672	525
10/75	547	575	620	604	681	687
11/75	16	720	688	70	720	593
12/75	172	660	709	0	689	547

Form #4

FGD SYSTEM RELIABILITY INFORMATION

System Phillips Module A,B,C,&D

	Hours Boiler Operated					
Month/ Year	Boiler #1	Boiler #2	Boiler #3	Boiler #4	Boiler #5	Boiler #6
1/76	222	722	639	0	662	661
2/76	445	588	672	0	633	571
3/76						
4/76						
5/76						
6/76						
7/76						
8/76						

Form #1

FGD SYSTEM RELIABILITY INFORMATION

System	LaCygne
Start-Up Date	2/73
Number of Modules	7
Size of Modules (ACFM)	340,000
Total System Operating Hours	
Total Boiler Hours in Period for which Data is Available	11,481
Total Hours System was Required to Operate	
Total Hours System was Available to Operate	
Longest Continuous System Operation	
Average Load on System per Operating Hour	
Maintenance Hours per Module per Week	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74	364		179		
2/74	364		239		
3/74	0	0	0		
4/74	332		222		
5/74	500		344		
6/74	480		441		
7/74	313		236		
8/74	571		514		
9/74	606		417		
10/74	662		472		
11/74	386		347		
12/74	0	0	0		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75	0	0	0		
2/75	0	0	0		
3/75	694	41.1			613
4/75	0	0	0		
5/75	683	55.9			704
6/75	667	56.4			632
7/75	590	50.0			583
8/75	630	49.5			555
9/75	610	41.7			565
10/75	231	12.5			492
11/75	346	28.7			668
12/75	597	46.8			675

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76	618	50.7			638
2/76	594	55.4			654
3/76	643	56.7			687
4/76	0	0	0		
5/76	436				714
6/76					670
7/76					699
8/76					684

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74	364		115		
2/74	364		247		
3/74	0	0	0		
4/74	332		233		
5/74	500		415		
6/74	480		402		
7/74	313		252		
8/74	571		512		
9/74	606		532		
10/74	662		402		
11/74	386		273		
12/74	0	0	0		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75	0	0	0		
2/75	0	0	0		
3/75	694	41.1			714
4/75	0	0	0		
5/75	683	55.9			633
6/75	667	56.4			615
7/75	590	50.0			667
8/75	630	49.5			655
9/75	610	41.7			602
10/75	231	12.5			675
11/75	346	28.7			654
12/75	597	46.8			650

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76	618	50.7			630
2/76	594	55.4			628
3/76	643	56.7			667
4/76	0	0	0		
5/76	436				684
6/76					677
7/76					707
8/76					692

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE C

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74	364		161		
2/74	364		213		
3/74	0	0	0		
4/74	332		249		
5/74	500		390		
6/74	480		400		
7/74	313		256		
8/74	571		415		
9/74	606		444		
10/74	662		391		
11/74	386		230		
12/74	0	0	0		

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE C

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75	0	0	0		
2/75	0	0	0		
3/75	694	41.1			656
4/75	0	0	0		
5/75	683	55.9			701
6/75	667	56.4			604
7/75	590	50.0			667
8/75	630	49.5			649
9/75	610	41.7			607
10/75	231	12.5			344
11/75	346	28.7			577
12/75	597	46.8			602

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE C

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76	618	50.7			675
2/76	594	55.4			597
3/76	643	56.7			658
4/76	0	0	0		
5/76	436				692
6/76					677
7/76					684
8/76					685

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE D

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74	364		315		
2/74	364		278		
1/74	0	0	0		
4/74	332		293		
5/74	500		426		
6/74	480		433		
7/74	313		253		
8/74	571		460		
9/74	606		458		
10/74	662		535		
11/74	386		235		
12/74	0	0	0		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE D

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75	0	0	0		
2/75	0	0	0		
3/75	694	41.1			570
4/75	0	0	0		
5/75	683	55.9			666
6/75	667	56.4			611
7/75	590	50.0			623
8/75	630	49.5			580
9/75	610	41.7			610
10/75	231	12.5			548
11/75	346	28.7			671
12/75	597	46.8			634

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE D

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76	618	50.7			534
2/76	594	55.4			635
3/76	643	56.7			692
4/76	0	0	0		
5/76	436				714
6/76					677
7/76					692
8/76					699

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE E

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74	364		83		
2/74	364		189		
3/74	0	0	0		
4/74	332		245		
5/74	500		389		
6/74	480		393		
7/74	313		266		
8/74	571		463		
9/74	606		503		
10/74	662		520		
11/74	386		324		
12/74	0	0	0		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE 2

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75	0	0	0		
2/75	0	0	0		
3/75	694	41.1			692
4/75	0	0	0		
5/75	683	55.9			668
6/75	667	56.4			605
7/75	590	50.0			635
8/75	630	49.5			688
9/75	610	41.7			567
10/75	231	12.5			535
11/75	346	28.7			692
12/75	597	46.8			646

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE E

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76	618	50.7			624
2/76	594	55.4			638
3/76	643	56.7			701
4/76	0	0	0		
5/76	436				662
6/76					670
7/76					692
8/76					684

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE F

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74	364		133		
2/74	364		364		
3/74	0	0	0		
4/74	352		332		
5/74	500		422		
6/74	480		396		
7/74	313		248		
8/74	571		448		
9/74	606		539		
10/74	662		615		
11/74	386		327		
12/74	0	0	0		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE F

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75	0	0	0		
2/75	0	0	0		
3/75	694	41.1			681
4/75	0	0	0		
5/75	683	55.9			664
6/75	667	56.4			620
7/75	590	50.0			650
8/75	630	49.5			632
9/75	610	41.7			559
10/75	231	12.5			544
11/75	346	28.7			644
12/75	597	46.8			659

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE E

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76	618	50.7			612
2/76	594	55.4			648
3/76	643	56.7			679
4/76	0	0	0		
5/76	436				707
6/76					670
7/76					699
8/76					670

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE G

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74	364		295		
2/74	364		237		
3/74	0		0		
4/74	332		291		
5/74	500		399		
6/74	480		418		
7/74	313		241		
8/74	571		507		
9/74	606		518		
10/74	662		588		
11/74	386		323		
12/74	0		0		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE G

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75	0	0	0		
2/75	0	0	0		
3/75	694	41.1			665
4/75	0	0	0		
5/75	683	55.9			620
6/75	667	56.4			638
7/75	590	50.0			634
8/75	630	49.5			618
9/75	610	41.7			534
10/75	231	12.5			481
11/75	346	28.7			676
12/75	597	46.8			622

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM La Cygne MODULE G

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76	618	50.7			627
2/76	594	55.4			658
3/76	643	56.7			680
4/76	0	0	0		
5/76	436				714
6/76					655
7/76					699
8/76					655

Form #1

FGD SYSTEM RELIABILITY INFORMATION

System	Green River
Start-Up Date	9/13/76
Number of Modules	1
Size of Modules (ACFM)	360,000
Total System Operating Hours	5426
Total Boiler Hours in Period for which Data is Available	5201
Total Hours System was Required to Operate	6049
Total Hours System was Available to Operate	
Longest Continuous System Operation	
Average Load on System per Operating Hour	
Maintenance Hours per Module per Week	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Green River MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75					
2/75					
3/75					
4/75					
5/75					
6/75					
7/75					
8/75					
9/75			139		
10/75			149		
11/75			146		
12/75	398		257	331	550

Form #3

FCD SYSTEM RELIABILITY INFORMATION

SYSTEM Green River MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76	572		64	456	312
2/76	499		211	499	486
3/76	450		386	409	722
4/76	552		552	552	648
5/76	456		456	456	606
6/76	597		589	596	720
7/76	587		577	587	666
8/76	744		722	744	722
9/76	571		571	571	617

Form #1

FGD SYSTEM RELIABILITY INFORMATION

System	Paddy's Run
Start-Up Date	4/73
Number of Modules	2
Size of Modules (ACFM)	175,000 (355°F)
Total System Operating Hours	
Total Boiler Hours in Period for which Data is Available	
Total Hours System was Required to Operate	
Total Hours System was Available to Operate	
Longest Continuous System Operation	
Average Load on System per Operating Hour	
Maintenance Hours per Module per Week	

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Paddy's Run MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
4/73	320		60		
5/73	267		30		
6/73	253		3		
7/73	238		50		
8/73	330		175		
9/73	388		333		
10/73	682		340		
11/73	720		249		
12/73	192		83		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Paddy's Run MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Operability(%)	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74			0		
2/74			0		
3/74			0		
4/74			0		
5/74			0		
6/74			0		
7/74			51		
8/74			50		
9/74			0		
10/74			100		
11/74			0		
12/74			0		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Paddy's Run MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Operability(%)	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75			0		
2/75			0		
3/75			0		
4/75			0		
5/75			0		
6/75			0		
7/75			0		
8/75			0		
9/75			100		
10/75			100		
11/75			100		
12/75			90		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Paddy's Run MODULE A

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Operability(%)	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76			100		
2/76			0		
3/76			0		
4/76			0		
5/76			100		
6/76			100		
7/76			100		
8/76			100		
9/76					
10/76					
11/76					
12/76					

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Paddy's Run MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Hours Module Operated	Hours Module Was Required to Operate	Hours Module Was Available to Operate
4/73	320		190		
5/73	267		175		
6/73	253		15		
7/73	238		50		
8/73	330		213		
9/73	388		279		
10/73	682		637		
11/73	720		720		
12/73	192		151		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Paddy's Run MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Operability(%)	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/74			0		
2/74			0		
3/74			0		
4/74			0		
5/74			0		
6/74			0		
7/74			81		
8/74			77		
9/74			0		
10/74			100		
11/74			0		
12/74			0		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Paddy's Run MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Operability(%)	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/75			0		
2/75			0		
3/75			0		
4/75			0		
5/75			0		
6/75			0		
7/75			0		
8/75			0		
9/75			100		
10/75			100		
11/75			100		
12/75			90		

Form #3

FGD SYSTEM RELIABILITY INFORMATION

SYSTEM Paddy's Run MODULE B

Month/ Year	Hours Boiler Operated	Generation Capacity (%)	Operability(%)	Hours Module Was Required to Operate	Hours Module Was Available to Operate
1/76			100		
2/76			0		
3/76			0		
4/76			0		
5/76			100		
6/76			100		
7/76			100		
8/76			100		

GRAPHICAL REPRESENTATION OF FGD SYSTEM PERFORMANCE

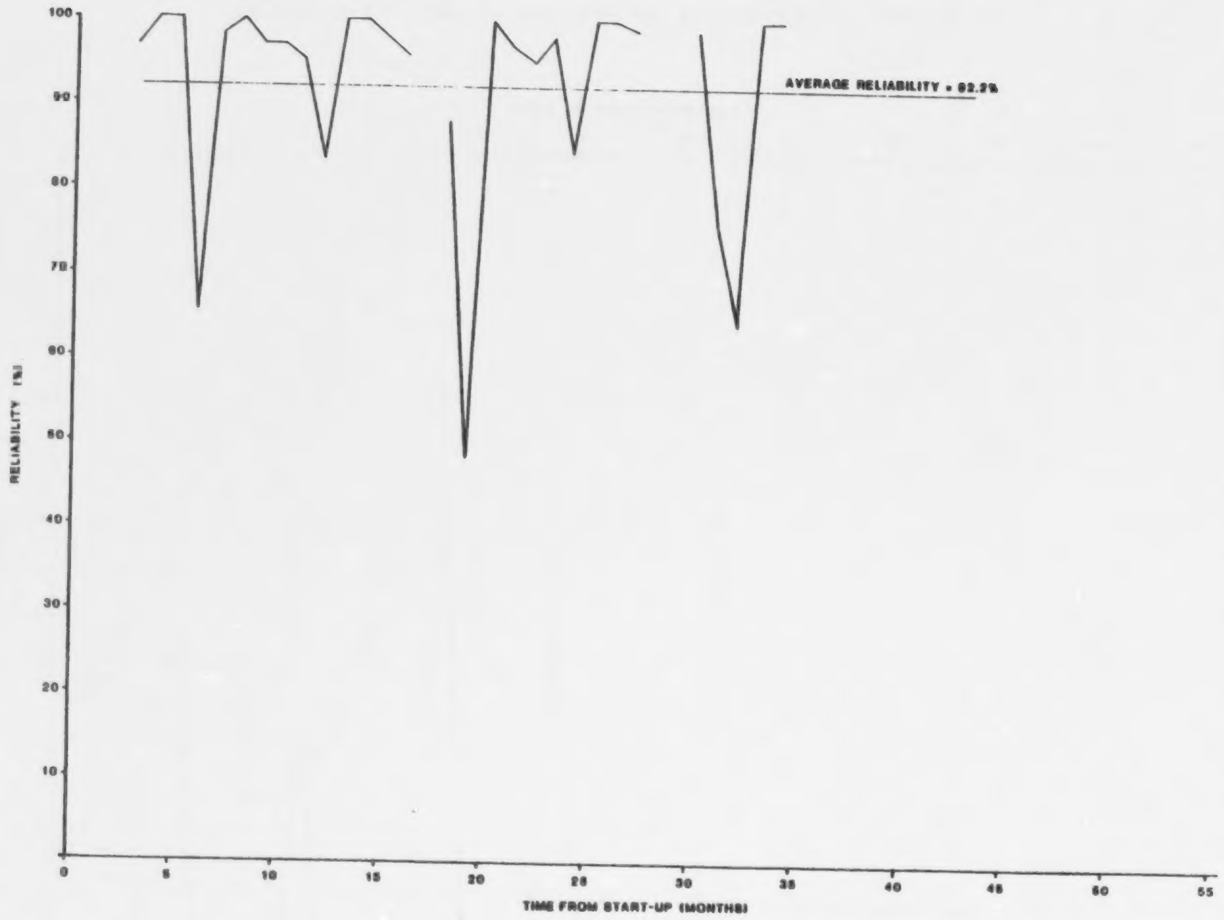

Figure C-1. Cholla FGD System Reliability - Module A.

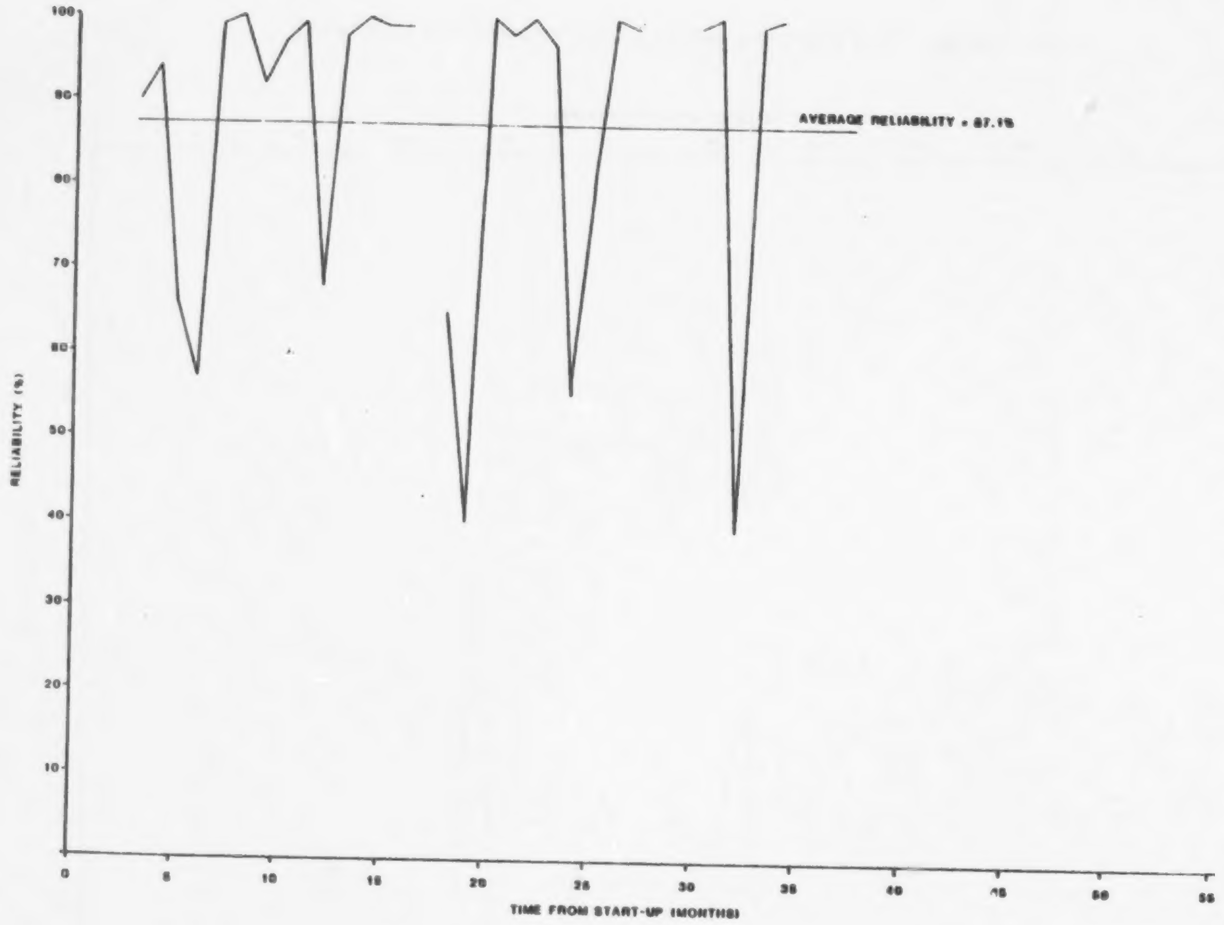

Figure C-2. Cholla FGD System Reliability - Module B.

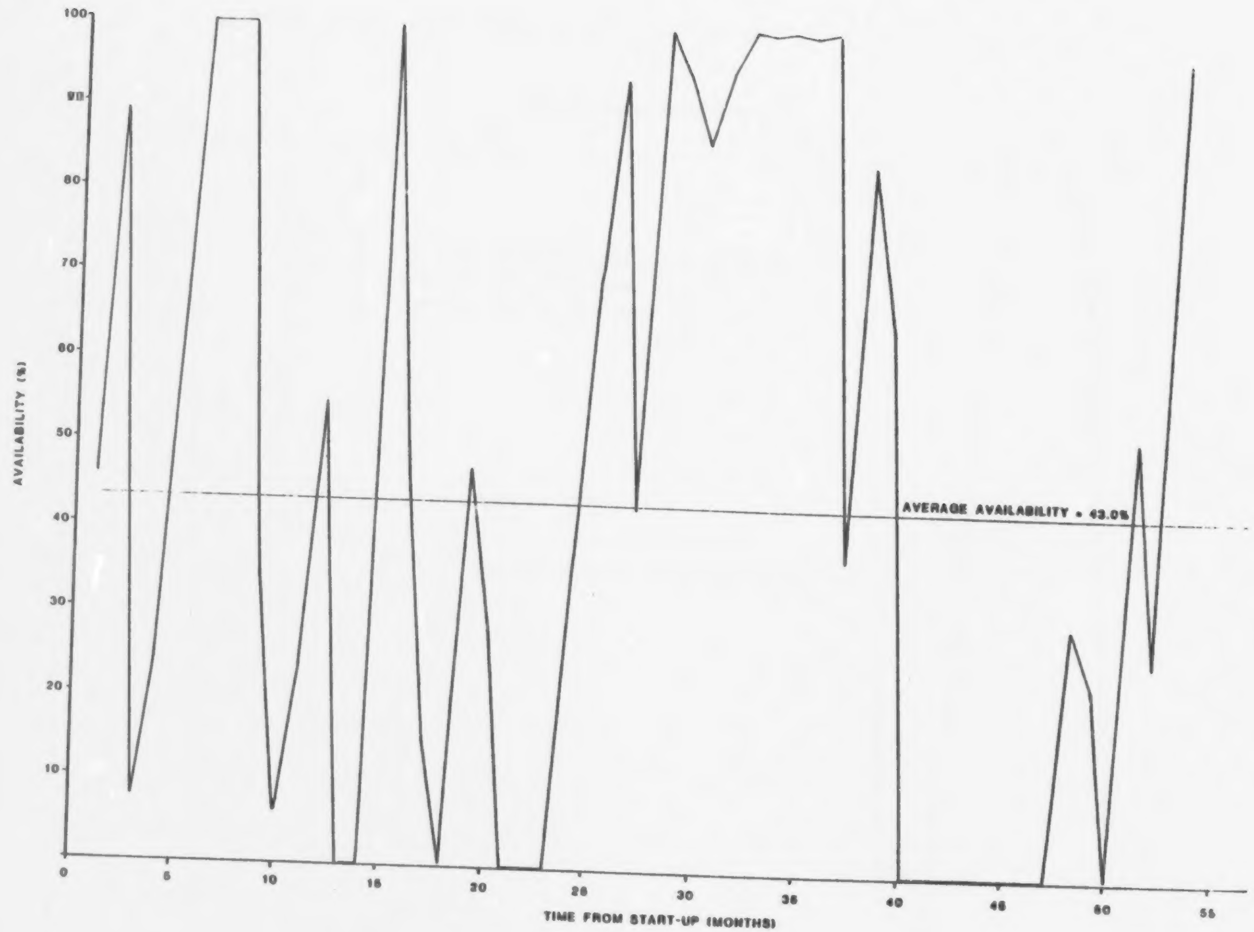

Figure C-3. Will County FGD System Availability - Module A.

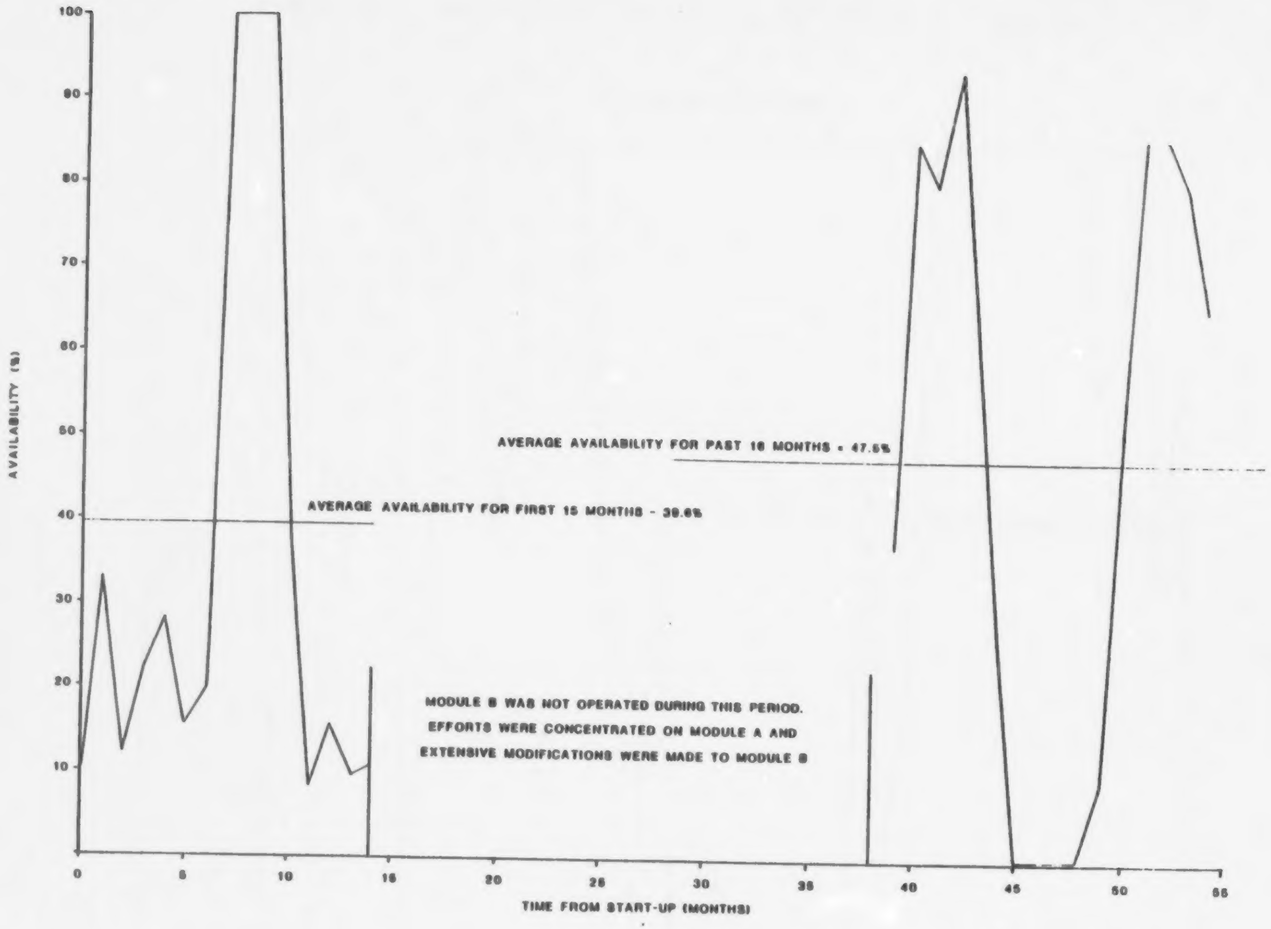

Figure C-4. Will County FGD System Availability - Module B.

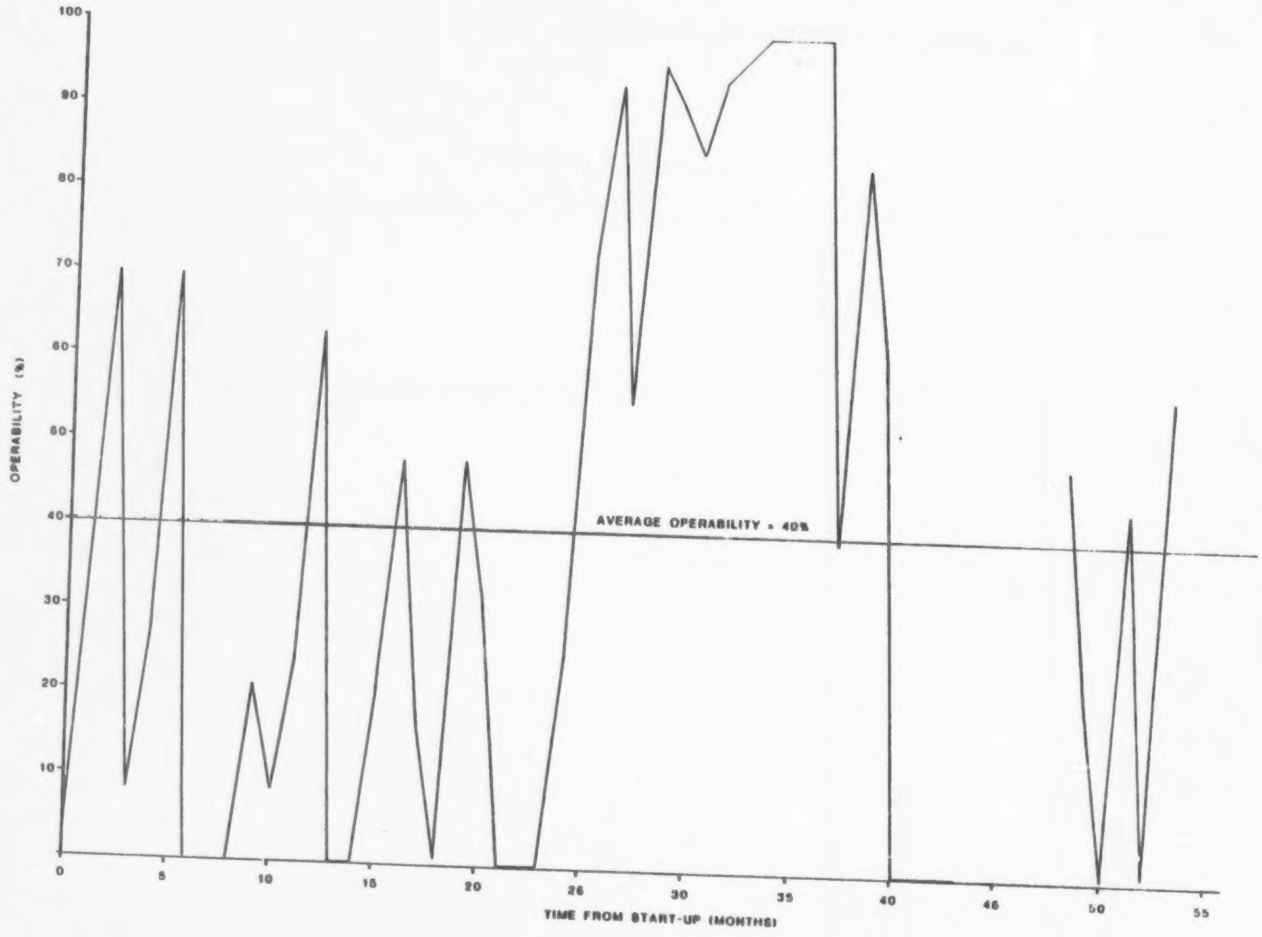

Figure C-5. Will County FGD System Operability - Module A.

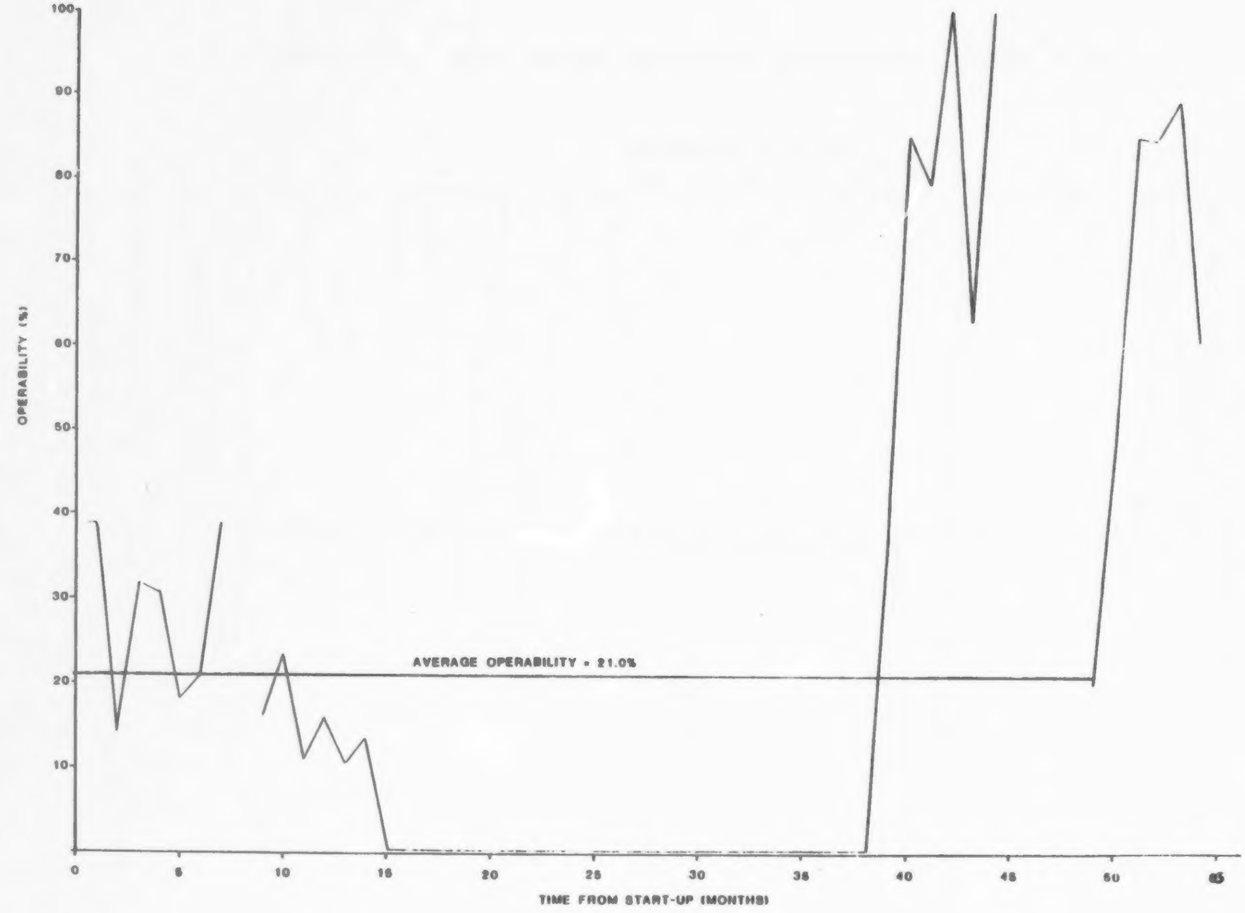

Figure C-6. Will County FGD System Operability - Module B.

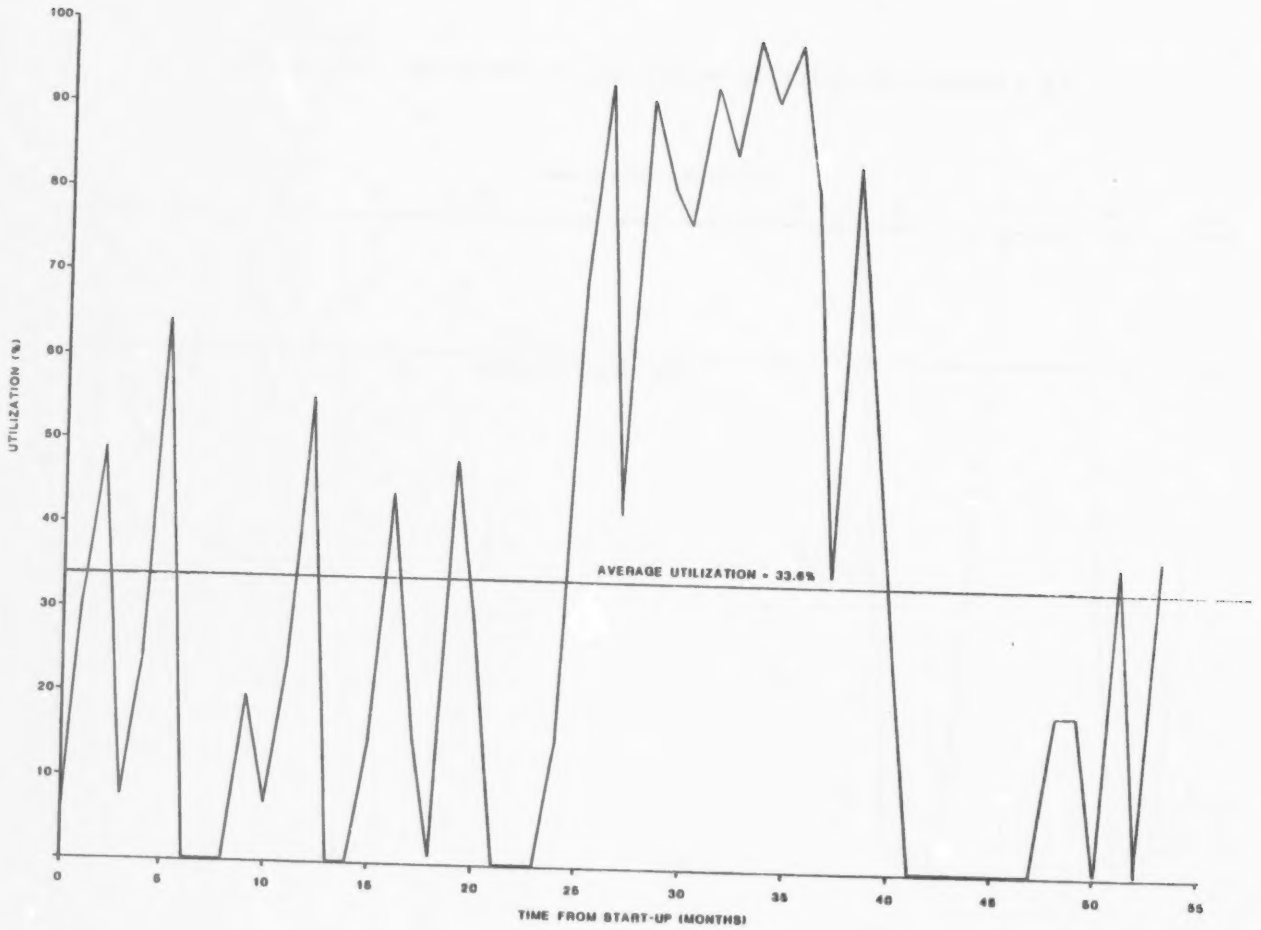

Figure C-7. Will County FGD System Utilization - Module A.

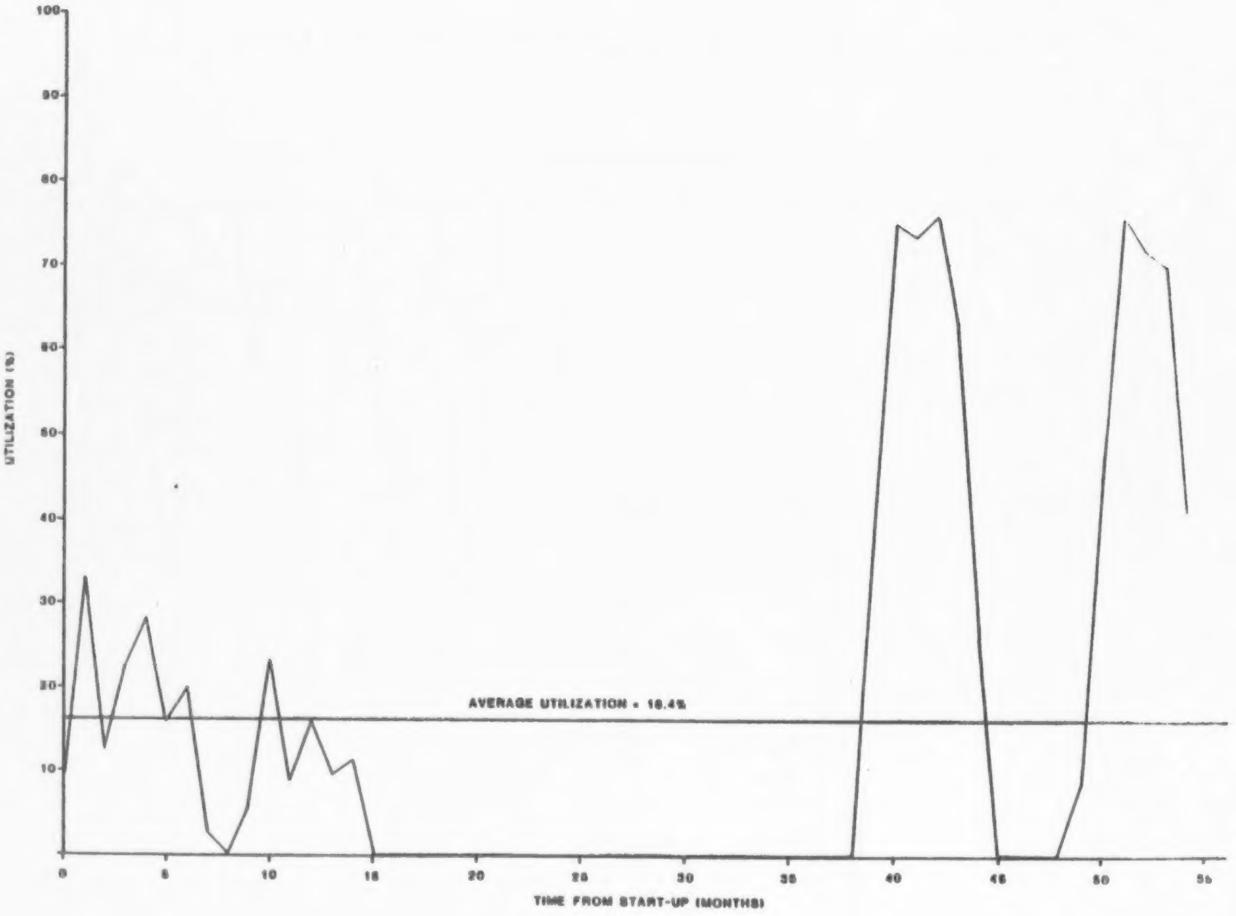

Figure C-8. Will County FGD System Utilization - Module B.

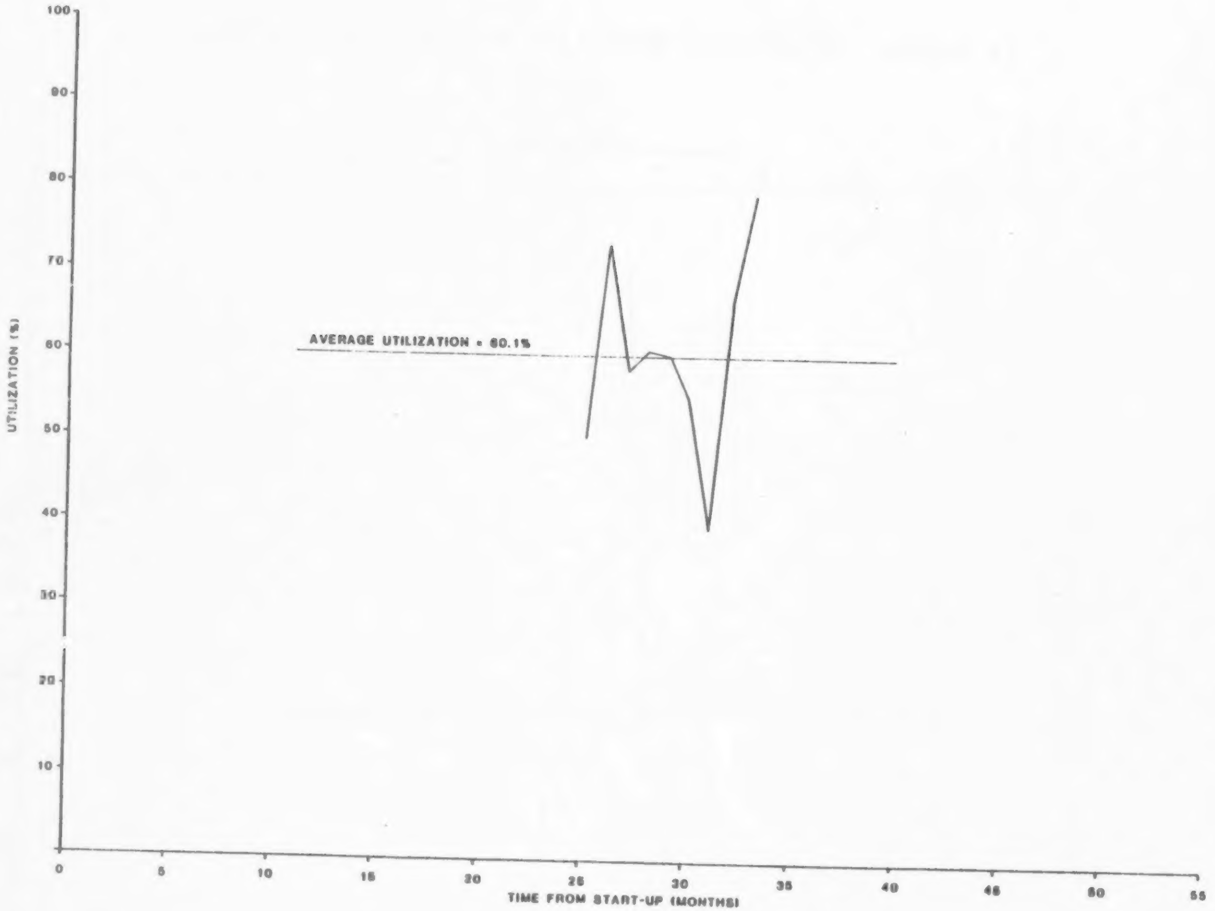

Figure C-9. Phillips FGD System Utilization - Average Modules A,B&C.

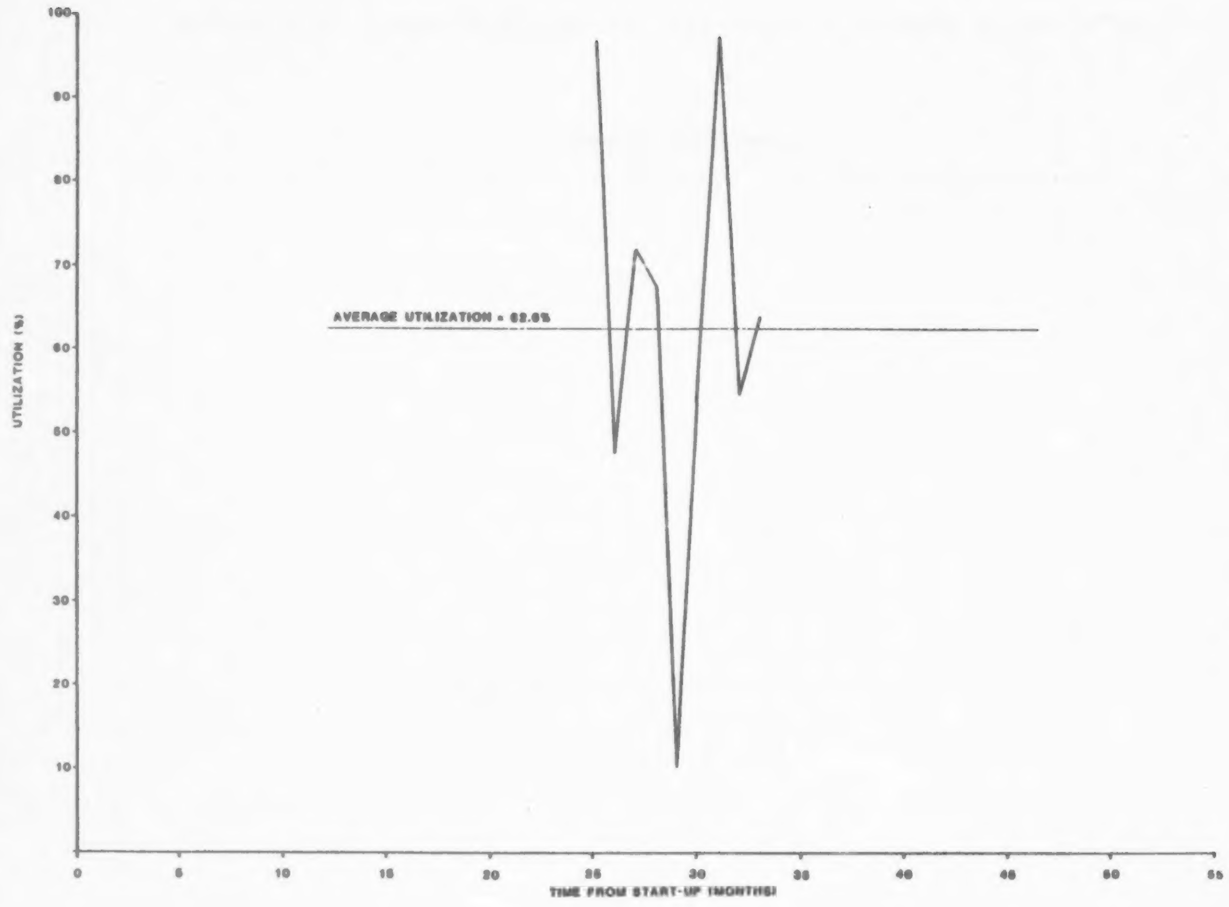

Figure C-10. Phillips FGD System Utilization - Module D.

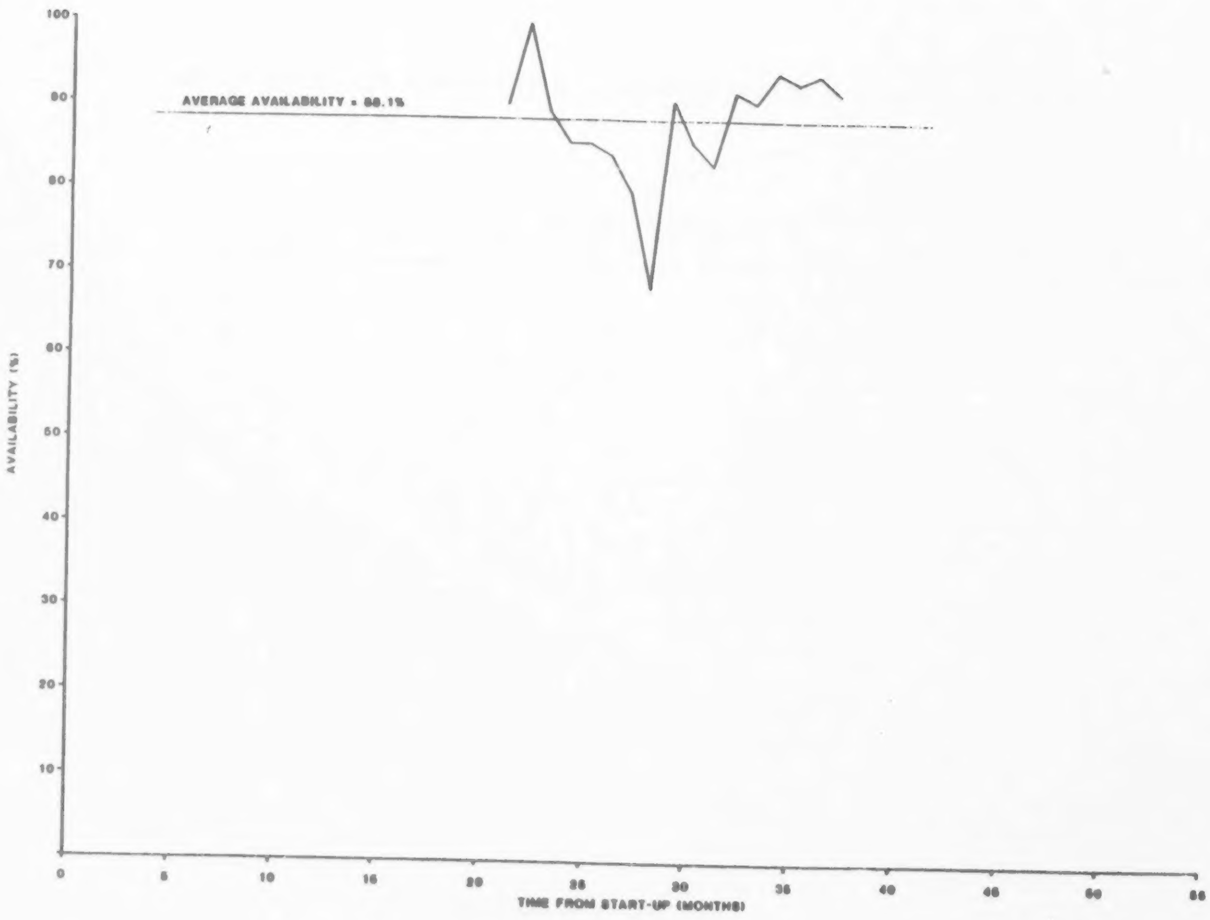

Figure C-11. La Cygne FGD System Availability - Average All Modules.

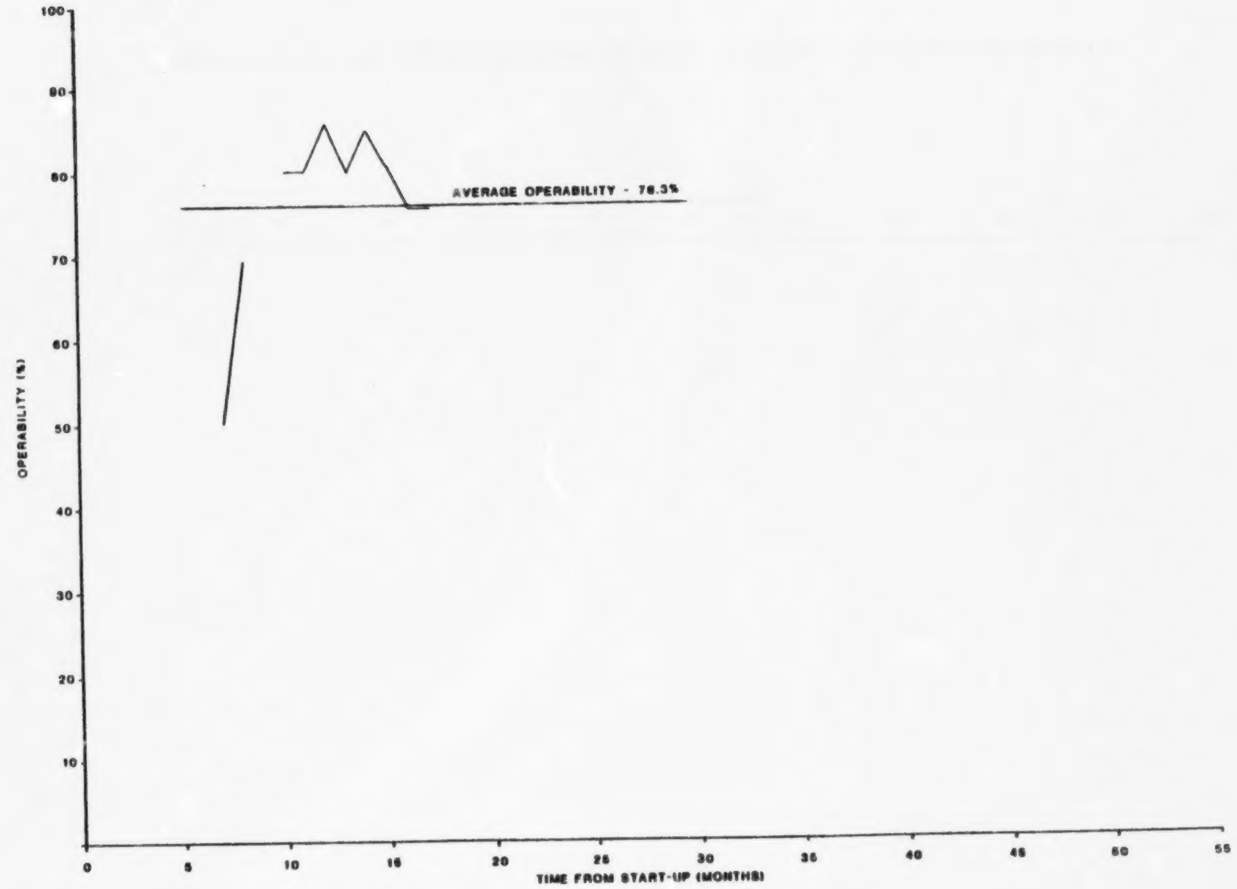

Figure C-12. La Cygne FGD System Operability - Average All Modules.

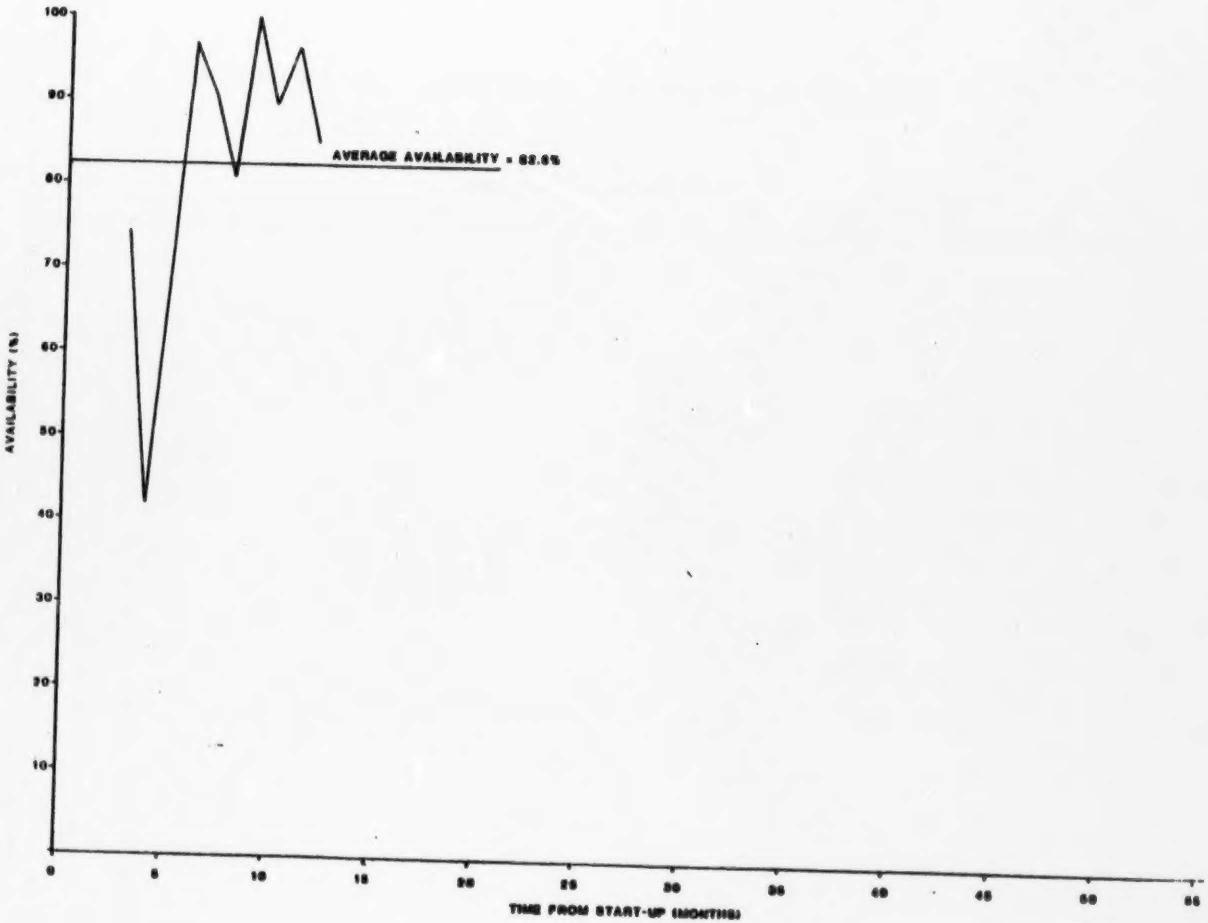

Figure C-13. Green River FGD System Availability.

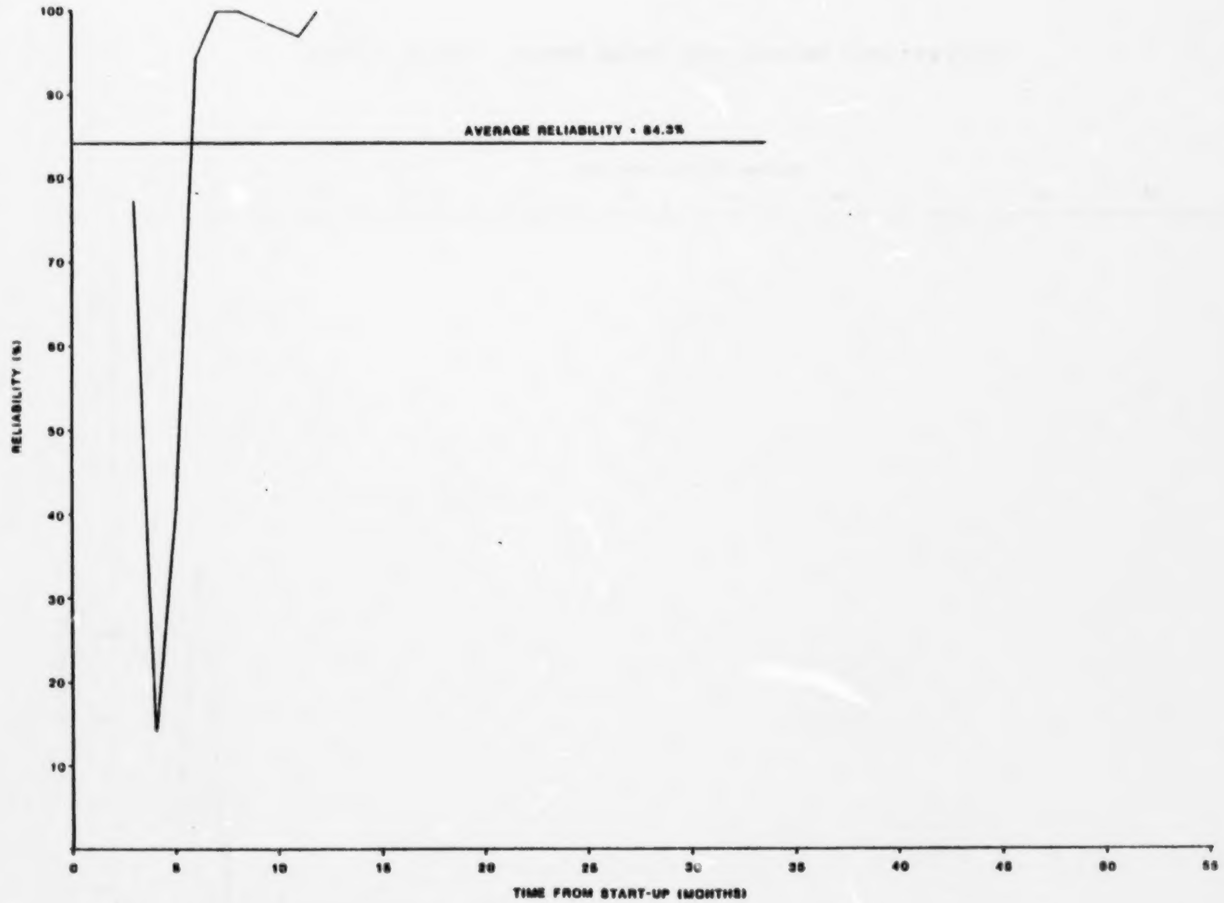

Figure C-14. Green River FGD System Reliability.

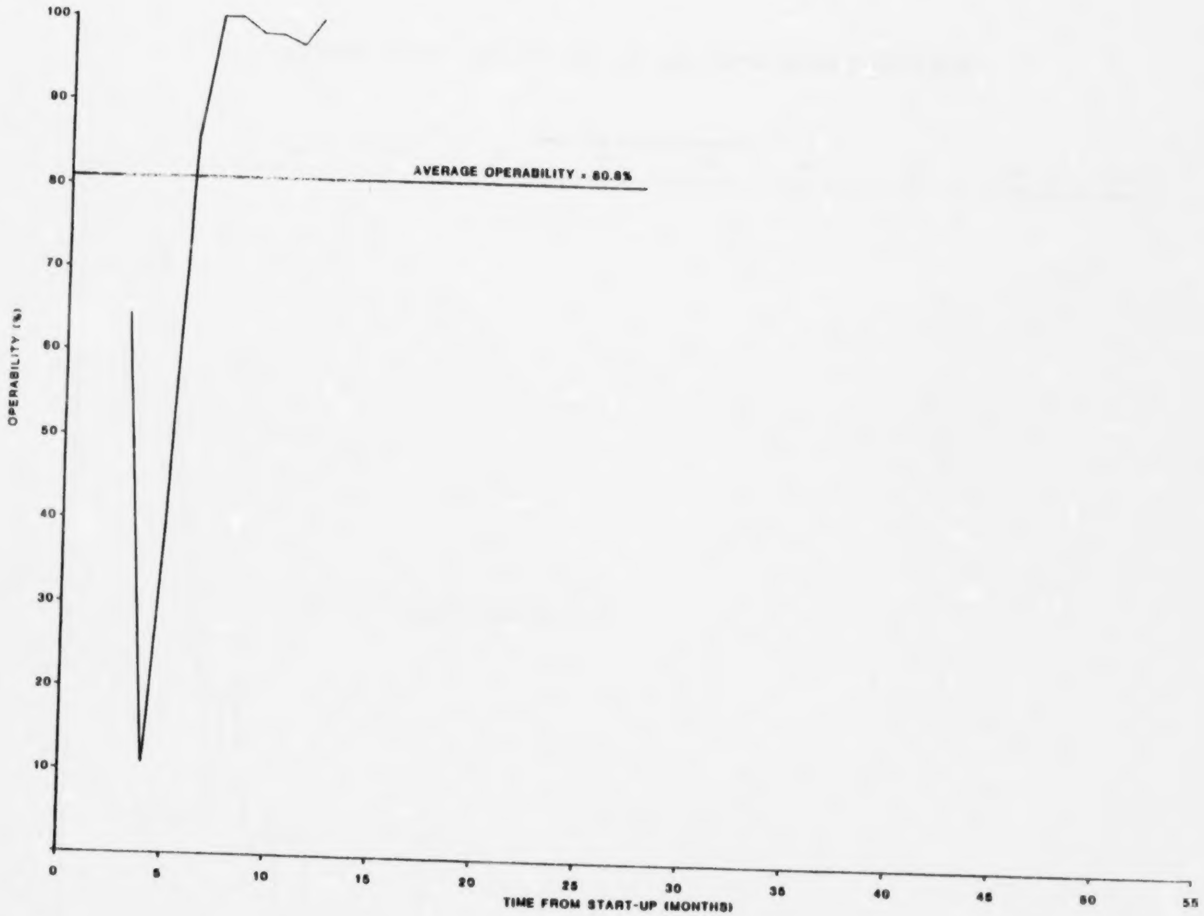

Figure C-15. Green River FGD System Operability.

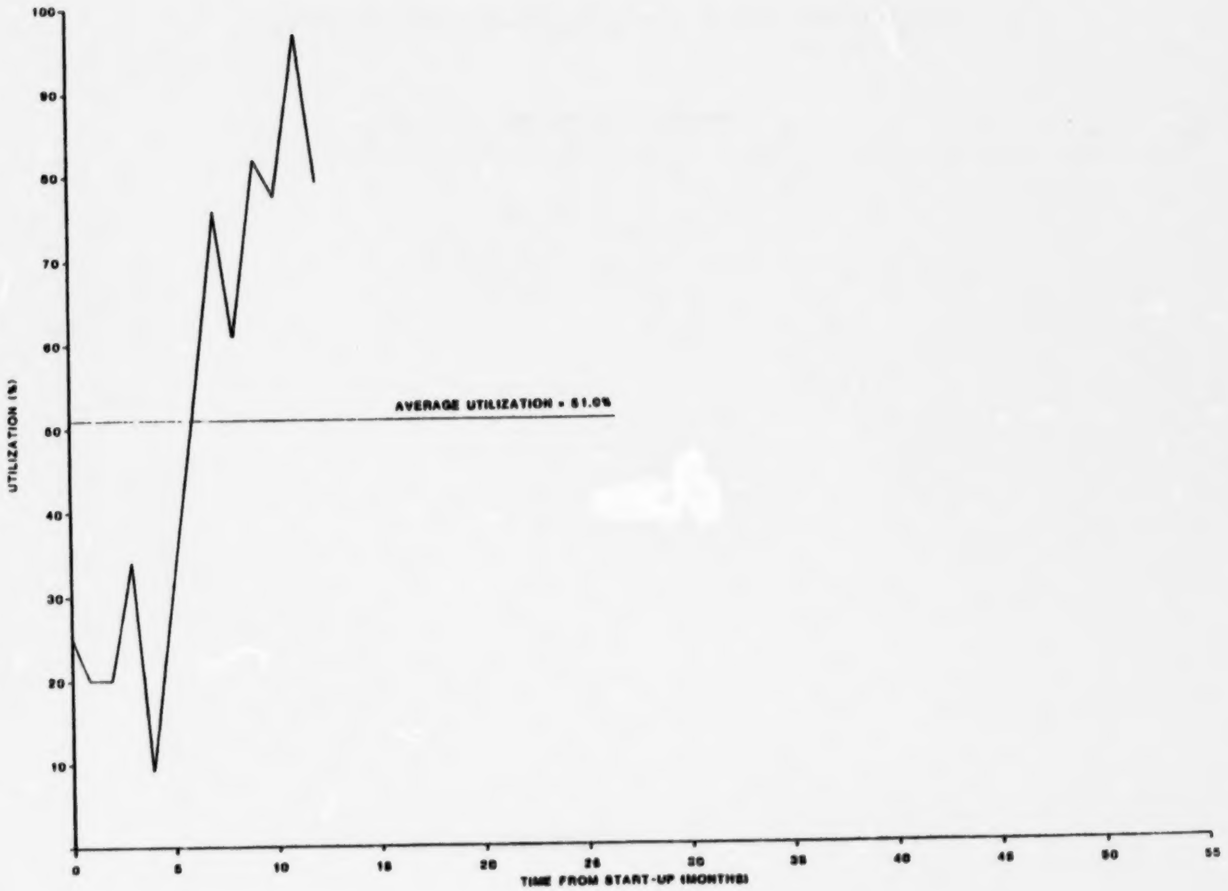

Figure C-16. Green River FGD System Utilization.

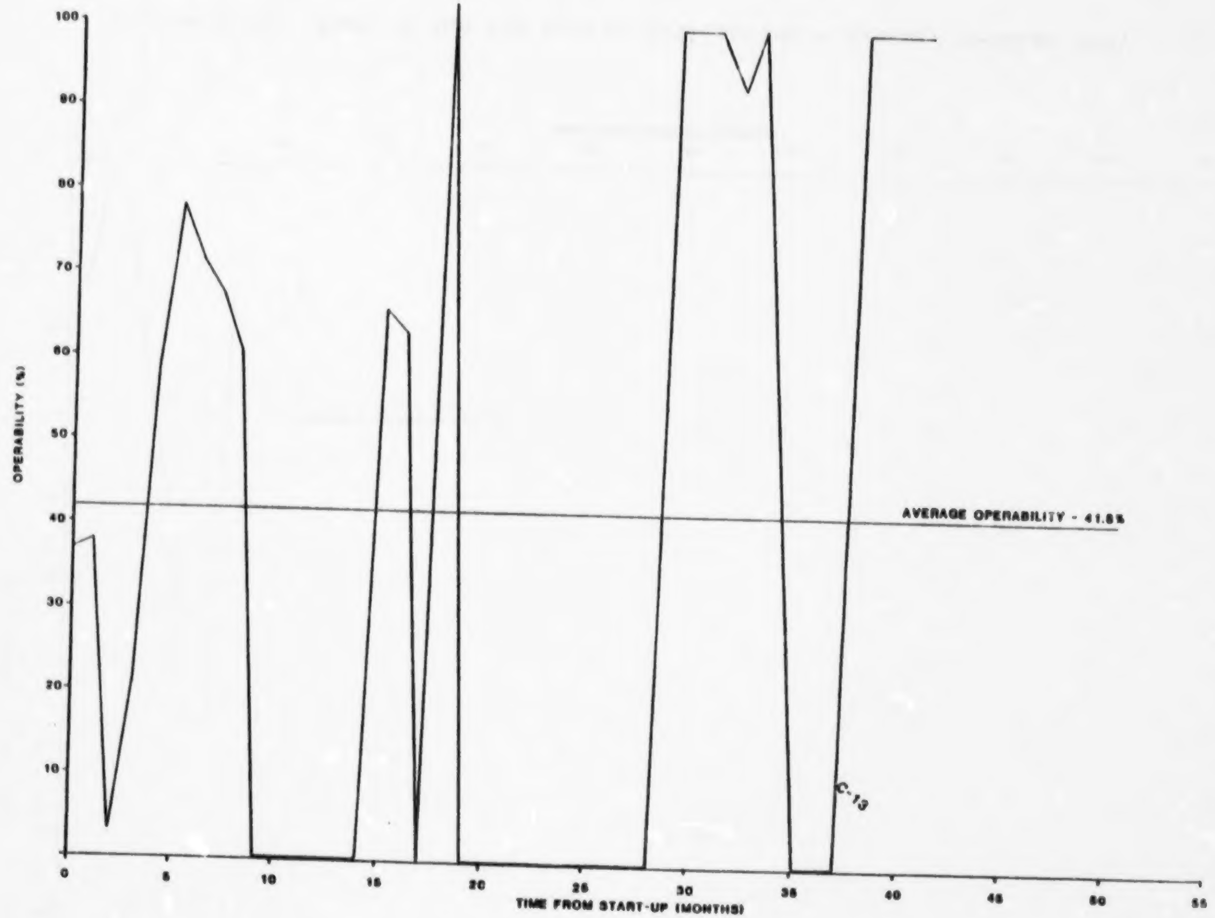

Figure C-17. Paddy's Run FGD System Operability - Average Modules A&B.

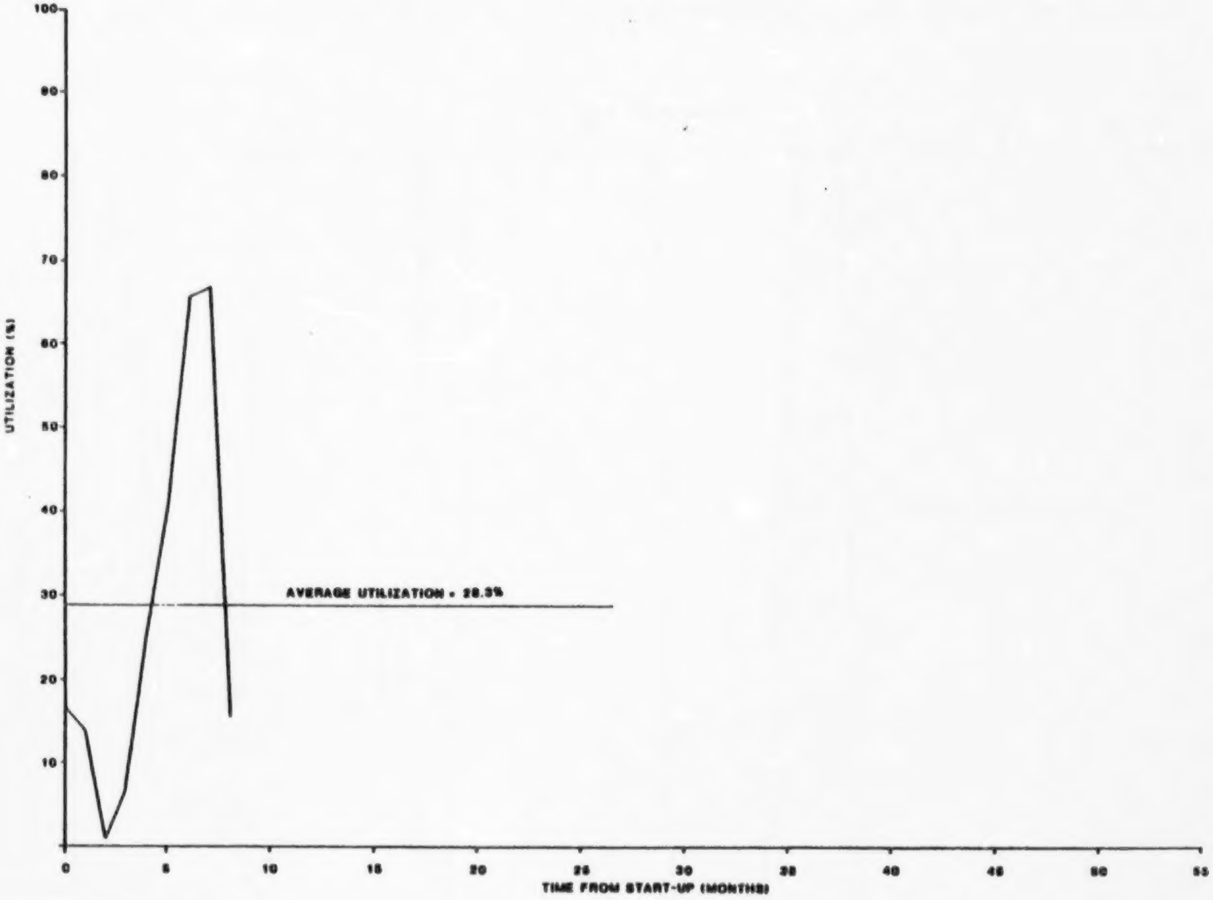

Figure C-18. Paddy's Run FGD System Utilization - Average Modules A&B.

CALCULATIONS

Availability Range

Availability = A

Will County = 43.55
LaCygne = 88.1
Green River = 82.6

Average = 71.35

$$\hat{\sigma}^2 = \tfrac{1}{2}\left[(43.35-71.35)^2 + (88.1-71.35) + (82.6-71.35)^2\right]$$

$$\hat{\sigma}^2 = \frac{784+280.6+126.6}{2} = 595.6$$

$$\hat{\sigma}^2 = 24.4$$

Case 1. 90% Confidence Level t = 2.92
99% Confidence Level t = 9.925

$$1. \quad \left(71.35 - \frac{(2.92)(24.4)}{\sqrt{3}}\right) \leq A \leq \left(71.35 + \frac{(2.92)(24.4)}{\sqrt{3}}\right)$$

$$30.2 \leq A \leq 100$$

$$2. \quad \left(71.35 - \frac{(9.925)(24.4)}{\sqrt{3}}\right) \leq A \leq \left(71.35 + \frac{(9.925)(24.4)}{\sqrt{3}}\right)$$

$$0 \leq A \leq 100$$

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Reliability Range

Reliability = R

Cholla	92.2
Green River	= 84.3
Average	= 88.25

$$\hat{\sigma}^2 = \left[(92.2-88.25)^2 + (84.3-88.25)^2\right]$$

$$\hat{\sigma}^2 = 15.6 + 15.6 = 31.2$$

$$\hat{\sigma}^2 \quad 5.6$$

Case 1. 90% Confidence Level t = 6.314

99% Confidence Level t = 63.66

$$1. \quad \left(88.25 - \frac{(6.314)(5.6)}{\sqrt{2}}\right) \leq R \leq \left(88.25 + \frac{(6.314)(5.6)}{\sqrt{2}}\right)$$

$$63.2 \leq R \leq 100$$

$$2. \quad \left(88.25 - \frac{(63.66)(5.6)}{\sqrt{2}}\right) \leq R \leq \left(88.25 + \frac{(63.66)(5.6)}{\sqrt{2}}\right)$$

$$0 \leq R \leq 100$$

Operability Range

Operability = 0

Will County = 20.5
Green River = 80.8
Paddy's Run = 41.8

Average = 47.7

$$\hat{\sigma}^2 = \tfrac{1}{2}\left[(20.5-47.7)^2 + (80.8-47.7)^2 + (41.8-47.7)^2\right]$$

$$\hat{\sigma}^2 = \tfrac{1}{2}\left[739.8 + 1095.6 + 34.8\right] = 935$$

$$\hat{\sigma}^2 = 30.57$$

Case 1. 90% Confidence Level t = 2.92
99% Confidence Level t = 9.925

1. $$\left(47.7 - \frac{(2.92)(30.57)}{\sqrt{3}}\right) \leq 0 \leq \left(47.7 + \frac{(2.92)(30.57)}{\sqrt{3}}\right)$$

$$0 \leq 0 \leq 99$$

2. $$\left(47.7 - \frac{(9.925)(30.57)}{\sqrt{3}}\right) \leq 0 \leq \left(47.7 - \frac{(9.925)(30.57)}{\sqrt{3}}\right)$$

$$0 \leq 0 \leq 100$$

Utilization Range

Utilization = U

Will County = 25.0
Phillips = 61.3
LaCygne = 76.3
Green River = 51.0
Paddy's Run = 28.3

Average = 48.4

$$\hat{\sigma}^2 = \tfrac{1}{4}\left[(25-48.4)^2 + (61.3-48.4)^2 + (76.3-48.4)^2 + (51-48.4)^2 + (28.3-48.4)^2\right]$$

$$\hat{\sigma}^2 = \tfrac{1}{4}\left[547.6 + 166.4 + 778.4 + 6.8 + 404\right] = 475.8$$

$$\hat{\sigma} = 21.8$$

Case 1. 90% Confidence Level t = 2.132
99% Confidence Level t = 4.604

$$1.\quad \left(48.4 - \frac{(2.132)(21.8)}{\sqrt{5}}\right) \leq U \leq \left(48.4 + \frac{(2.132)(21.8)}{\sqrt{5}}\right)$$

$$27.6 \leq U \leq 69.2$$

$$2.\quad \left(48.4 - \frac{(4.604)(21.8)}{\sqrt{5}}\right) \leq U \leq \left(48.4 + \frac{(4.604)(21.8)}{\sqrt{5}}\right)$$

$$3.5 \leq U \leq 93.3$$

APPENDIX D

FGD SYSTEMS

D.1 CHOLLA GENERATING STATION

The Cholla Power Generating Station of the Arizona Public Service Company is located near Joseph City, Arizona. The Cholla Station consists of a 126 MW coal-fired boiler which has been retrofitted with an FGD system. The boiler, which is of Combustion Engineering design and manufacture, has been in operation since 1962.

The FGD system is a limestone slurry scrubbing process which was designed by Research-Cottrell and placed in service in 1973. The system consists of two scrubbing modules, limestone slurrying equipment and a waste disposal pond. Figure D-1 is a schematic of the FGD system and Table D-1 illustrates the operating characteristics of the boiler-scrubber system.

A Research-Cottrell multicyclone collector is located between the boiler and the FGD system. This device operates with an efficiency of 75 percent to provide primary control of particulate emissions from the boiler.

The two scrubber modules which comprise the FGD system are each capable of processing 240,000 acfm or about 50 percent of the maximum flue gas flow from the boiler. However, the two modules are not identical. Module A consists of a flooded-disc venturi prescrubber in series with a packed tower absorber while Module B is comprised of an identical prescrubber in series with a spray tower absorber. Module A circulates limestone slurry in the absorber while the B absorber circulates makeup water.

Ground limestone for the FGD system is purchased from two suppliers, both located in Arizona. Because the plant has no limestone milling facility the finely ground limestone is stored in a silo. A small limestone slurry mixing tank is provided at the base of the tower.

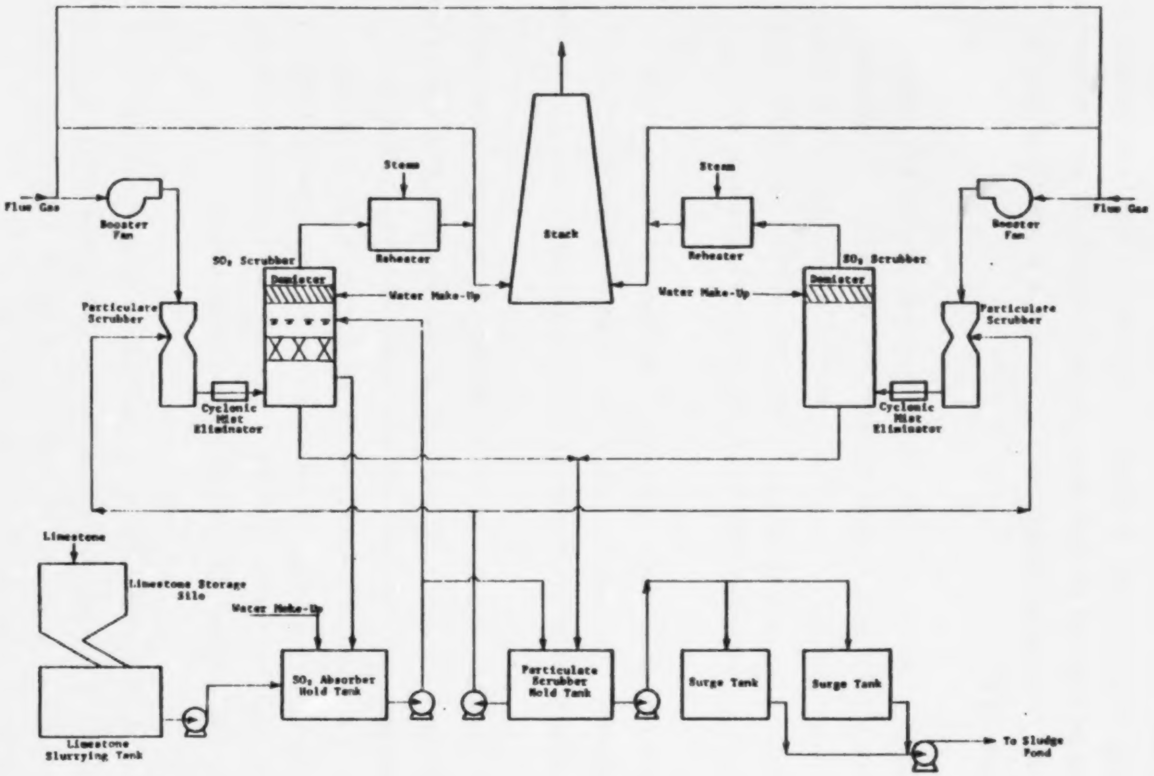

Flue Gas
Booster Fan
Particulate Scrubber
Cyclonic Mist Eliminator
SO_2 Scrubber
Demister
Water Make-Up
Steam
Reheater
Stack
Steam
Reheater
SO_2 Scrubber
Demister
Water Make-Up
Booster Fan
Flue Gas
Particulate Scrubber
Cyclonic Mist Eliminator
Limestone
Limestone Storage Silo
Water Make-Up
Limestone Slurrying Tank
SO_2 Absorber Hold Tank
Particulate Scrubber Hold Tank
Surge Tank
Surge Tank
To Sludge Pond

Figure D-1. Cholla FGD System.

TABLE D-1. OPERATING CHARACTERISTICS OF THE CHOLLA BOILER-SCRUBBER SYSTEM

Item	Description	Parameter	Value
1. Boiler	The power station has one dry-bottom pulverized-coal-fired boiler which has been operating since 1962. The unit is base load operated and has historically had trouble-free operation.	Power Rating Gross Net Without FGD Net With FGD Average Capacity Factor	 126 MW 115 MW 112 MW 90 percent
2. Fuel	A low-sulfur coal is burned at the power plant.	Sulfur Content Ash Content Heating Value	0.55 percent 10.4 percent 10,290 Btu/lb
3. Particulate Control	A Research-Cottrell multicyclone-type collector provides primary control of particulate emissions. The FGD system also removes particulates from the gas stream.	Removal Efficiency Multicyclone FGD system	 75 percent 97 percent
4. Absorbent/Preparation	Limestone is used to absorb SO_2 from the gas. Finely ground limestone is purchased from a mine near Kingman, Arizona. No milling facilities are at the Cholla station.	Composition Stoichiometry	- 1.1
5. SO_2 Control	The FGD system is used to control SO_2 emissions in order to comply with air quality regulations.	Removal Efficiency	58.5 percent
6. FGD System	The FGD system consists of two scrubbing modules (A and B), each handling 50 percent of the boiler's flue gas load. Module A is packed and circulates limestone slurry Module B is a spray-tower which circulates make-up water.	System Vendor Type Start-up Date Prescrubber type Module Size	Research-Cotrell Retrofit 7/73 Flooded-Disc, Variable Throat Venturi 260,000 acfm @ 276°F
7. Demister	A two-stage, polypropylene slat demister is located in the upper section of both A and B absorbers. The demisters are washed intermittently from above and below with fresh water sprays	Demister wash	-
8. Fan	A forced-draft booster fan is located upstream of the venturi prescrubber on each module.	System Pressure Drop	25 in H_2O
9. Reheater	The desulfurized flue gas is reheated as it passed through two shell-and-tube heat exchangers. Heat is supplied by 200 psig steam.	Flue Gas Temperature Inlet Outlet	 121°F 165°F
10. Sludge Disposal	The plant has no sludge treatment or fixation systems. The sludge is pumped to the fly ash disposal pond on an intermittent basis. Because of light rainfall and a high evaporation rate in this area, no liquor is recirculated from the pond.	Pond/Landfill Requirements	-
11. Water Make-Up	No water is recycled from the sludge disposal pond to the FGD system. Make-up water for the system is boiler water blowdown.	Fresh Water Make-Up	-

Flue gas entering the FGD system is split between the two modules. Most of the particulates remaining in the gas are removed by the prescrubbers. In the A absorber, flue gas flows through packing made of corrugated sheets of polypropylene. The packing promotes intimate contact between the flue gas and the circulating limestone slurry. Approximately 92 percent of the SO_2 in the flue gas which enters Module A is absorbed by the slurry. In the B absorber, flue gas is contacted with water sprays which absorb about 25 percent of the SO_2 which enters the module.

Overall, the Cholla FGD system removes nearly 58 percent of the flue gas SO_2. However, since the boiler is burning 0.55 percent sulfur coal, the quantity of SO_2 scrubber is only about 12 lbs SO_2 per ton of coal burned. This compares to other FGD systems which remove 72 to 180 lbs SO_2 per ton of coal burned.

Prior to leaving the absorbers, the flue gas passes through a two-stage demister which removes entrained droplets from the gas stream. The demisters are washed intermittently with fresh water to prevent plugging.

Spent scrubbing liquor from both modules is pumped to a recirculation tank. Most of this is recycled to the venturi prescrubbers. However, a purge stream is intermittently withdrawn from the recirculation tank and pumped directly to the sludge disposal pond.

A unique feature of the Cholla FGD system is its open loop mode of operation. This means that no water is recycled from the sludge pond to the scrubbing system. This type of operation is possible because of the high evaporation rate at the plant site.

Operation in the open loop mode reduces the possibility of sulfite/sulfate scaling in the FGD system. This in turn results in more reliable FGD system performance.

D.2 WILL COUNTY GENERATING STATION

The Will County Power Generating Station of Commonwealth Edison Company is located on the Chicago Sanitary and Ship Canal near the town of Romeoville, Illinois. An FGD system has been retrofitted on Unit No. 1 at the Will County Station. This unit is a 167 MW, wet-bottom, coal-fired boiler which was manufactured by Babcock and Wilcox and installed in 1955. The boiler is a cycling-load unit with an average capacity factor of 53 percent.

The FGD system is a limestone slurry scrubbing process designed and manufactured by Babcock and Wilcox and placed in service in February, 1972. The system consists of two scrubber modules, limestone handling and milling facilities, and a sludge treatment and stabilization unit. The system operates closed-loop with respect to process water. Fresh water is used only to replace evaporative losses and water retained in the sludge.

Flue gas flows from Unit 1, through an ESP, to the FGD system. The ESP, which has an actual removal efficiency of 79 percent, is used only when the FGD system is out of service.

Flue gas enters the FGD system and is split between the two scrubber modules. Each module is designed for 385,000 acfm throughput which is equivalent to one-half of the maximum flue gas flow from the boiler. The scrubber modules are comprised of a venturi prescrubber in series with a two-stage perforated tray absorption tower. Figure D-2 is a schematic of the FGD system and Table D-2 details the operating characteristics of the Will County boiler-scrubber system.

The flue gas entering the FGD system first flows through the venturi prescrubber. In the venturi, most of the particulates are removed from the gas as it is contacted with jets of limestone slurry sprayed from high pressure nozzles.

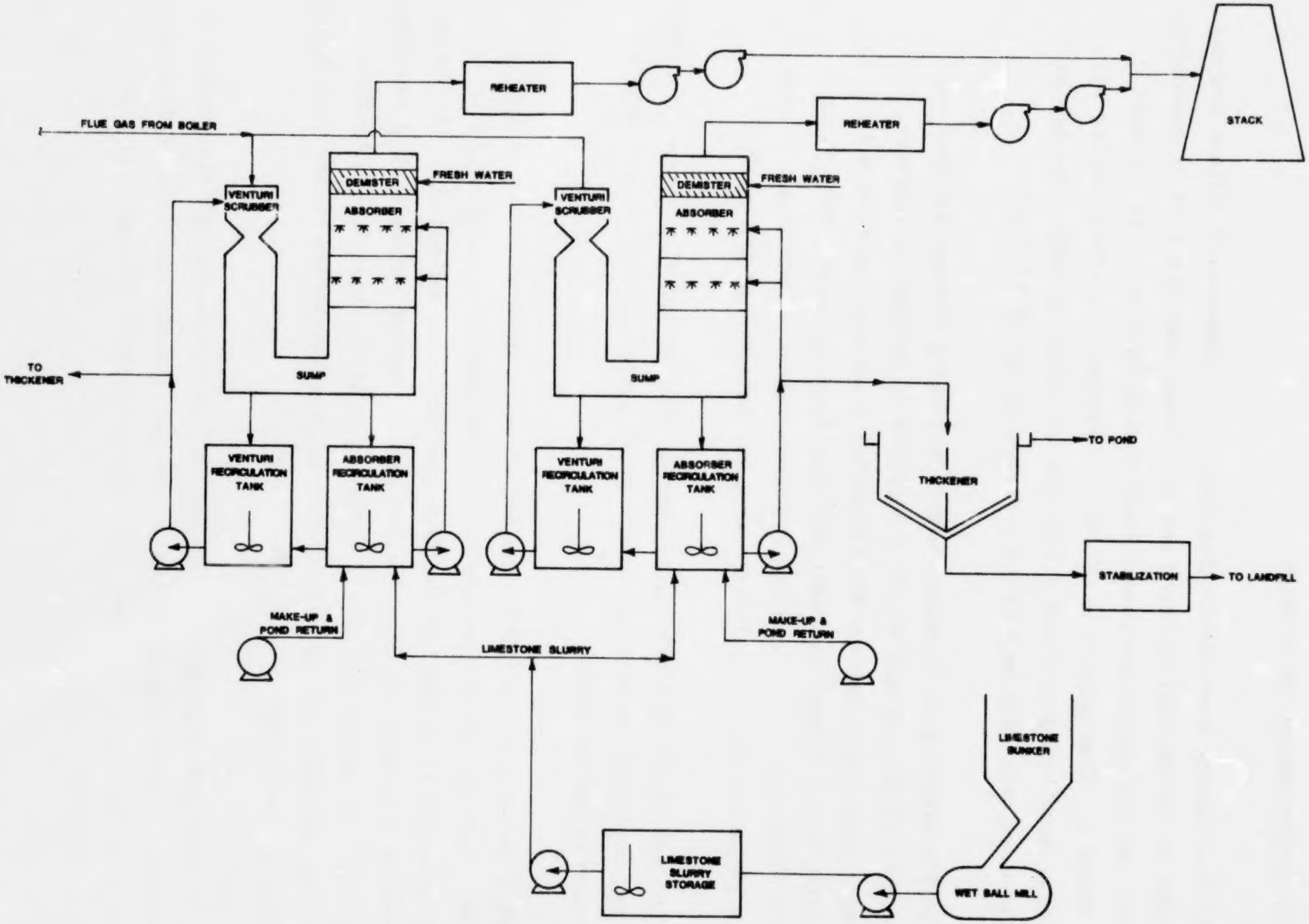

FLUE GAS FROM BOILER
VENTURI SCRUBBER
DEMISTER
ABSORBER
FRESH WATER
SUMP
TO THICKENER
VENTURI RECIRCULATION TANK
ABSORBER RECIRCULATION TANK
MAKE-UP & POND RETURN
LIMESTONE SLURRY
REHEATER
VENTURI SCRUBBER
DEMISTER
ABSORBER
FRESH WATER
SUMP
VENTURI RECIRCULATION TANK
ABSORBER RECIRCULATION TANK
MAKE-UP & POND RETURN
REHEATER
STACK
THICKENER
TO POND
STABILIZATION
TO LANDFILL
LIMESTONE BUNKER
WET BALL MILL
LIMESTONE SLURRY STORAGE

Figure D-2. Will County FGD System.

TABLE D-2. OPERATING CHARACTERISTICS OF THE WILL COUNTY UNIT NO. 1 BOILER-SCRUBBER SYSTEM

Item	Description	Parameter	Value
1. Boiler	Unit No. 1 of the Will County Power Generating Station is a wet-bottom, coal-fired boiler which has been retrofitted with an FGD system. The boiler was manufactured by Babcock and Wilcox and installed in 1955.	Power Rating	
		Gross	167 MW
		Net Without FGD	153 MW
		Net With FGD	146 MW
2. Fuel	Medium Sulfur Coal	Average Capacity Factor	52.8 Percent(1973)
		Sulfur Content	2.14 Percent
		Ash Content	10.0 Percent
		Heating Value	9463 Btu/lb
3. Particulate Control	The FGD system is used as the primary means of controlling particulates. An electrostatic precipitator-(ESP) manufactured by Joy Western Precipitation Division is used when the FGD system is inoperable.	Removal Efficiency	
		FGD System	98.0 Percent Removal
		ESP	79.0 Percent Removal
4. Absorbent Preparation	Limestone slurry absorbs SO_2 from the flue gas. The limestone milling facilities consist of a limestone rock conveyer, two 260-ton limestone bunkers, two wet ball mills, and a slurry storage tank.	Composition	
		Silica	0.5 Percent
		Calcium Carbonate	97.5 Percent
		Magnesium Carbonate	1.0 Percent
		Other	1.0 Percent
		Stoichiometry	1.3 - 1.5
5. SO_2 Control	The FGD system is used to control SO_2 emissions in order to meet air quality regulations.	Removal Efficiency	82 - 90 Percent
6. FGD System	The FGD system consists of two identical modules, each capable of processing 50 percent of the maximum flue gas flow from the boiler. The FGD modules are comprised of a venturi prescrubber in series with a two-stage perforated tray absorber.	System Vendor	Babcock and Wilcox
		Type	Retrofit
		Start-up Date	
		Module A	4/72
		Module B	2/72
		Prescrubber Type	Variable Throat Venturi
		Module Size	385,000 acfm @ 355°F
7. Demister	A two-stage, chevron-type demister is located 7 feet above the second absorber-tray. The demister is washed continuously from below and intermittently from above. Demisters are constructed of fiber reinforced plastic.	Demister Wash	
		Top	3,000 gpm Pond Supernatant/ 40 sec. every hr.
		Bottom	120 gpm Fresh Water/Continuous
8. Fan	There is an induced draft (ID) fan located at the reheater outlet on each module. These ID fans are in series with the boiler ID fans.	System Pressure Drop	25 in. H_2O

TABLE D-2. (Continued)

Item	Description	Parameter	Value
9. Reheater	The gas exiting the absorber is reheated by a bare tube reheater comprised of 9 sections. The bottom three sections are stainless steel and the other six sections are of corten steel construction. Each reheater has four soot blowers. Heat is supplied by saturated steam at 350 psig pressure.	Flue Gas Temperature Inlet Outlet	 128°F 165°F
10. Sludge Disposal	Sludge is fixed by mixing with lime and fly ash. Approximately 200 lbs of lime and 400 lbs of fly ash are required to stabilize 1 ton of sludge (dry basis).	Pond/Landfill Requirements	150 Acre - ft/yr
11. Water Makeup	Both fresh water and recycle pond water are used in the system. However, it is a closed-loop system.	Fresh Water Makeup	300 gpm

After passing through the venturi, the flue gas enters a sump where entrained slurry droplets are removed. The gas then flows upward through the SO_2 absorption tower and passes through two perforated trays. The trays, which are wetted with limestone slurry sprays, provide an extended wetted surface for absorption of SO_2 by the circulated slurry.

The absorption tower is fitted with a two-stage, Z-shaped demister. As flue gas flows through the demister, fine mist droplets coalesce on the surface of the demister vanes and drip back into the tower. The demister is equipped with two sets of wash water headers. The lower demister is washed continuously from below by 125 gpm of fresh water. It is also washed intermittently from above by 3000 gpm of pond water for 30 seconds every two hours.

Flue gas leaves the absorber/demister and enters the reheater unit, where its temperature is raised from 128°F to about 165°F. Reheat is necessary to prevent condensation in the fans, ducts, and the existing bricklined stack. The reheat also imparts plume buoyancy to suppress plume visibility.

Limestone for the FGD system is received in coarse ground form and is finely ground in two wet ball mills. A limestone slurry is discharged from the mills and piped to a storage tank which supplies the scrubber modules. Spent limestone slurry is withdrawn continuously from the venturi recirculation loop (Figure D-2) and discharged to a 65 foot diameter thickener. Thickener overflow is pumped directly to the scrubber sludge pond while the underflow is stabilized by mixing it with lime and fly ash. Overflow from the sludge pond is then returned to the recirculation tanks for reuse in the system. The stabilized sludge is transported by concrete mixing trucks to a small, on site, clay-lined basin where it solidifies in about one week.

D.3 PHILLIPS GENERATING STATION

The Phillips Power Generating Station of the Duquesne Light Company is located on the Ohio River, 20 miles northwest of Pittsburgh, Pennsylvania. The Phillips Station consists of six dry-bottom, pulverized-coal-fired boilers which have a generating capacity of 413 MW. All of the boilers were manufactured by Foster-Wheeler and installed during the period 1942 to 1957. The entire Phillips Station has been retrofitted with a Chemico FGD system which began operation in July, 1973.

The FGD system consists of four venturi scrubbers, a second stage SO_2 absorber, line slaking equipment, and sludge treatment and disposal facilities. The FGD system is supplemented by particulate removal equipment. This equipment consists of Research-Cottrell mechanical collectors in series with a Research-Cottrell ESP on each boiler. Figure D-3 is a schematic of the FGD system and Table D-3 details the operating characteristics of the Phillips boiler-scrubber system.

In operation, flue gas from the six boilers is treated by the particulate collection equipment and then routed into a common duct. The four venturi scrubbers are tied into this same duct to provide for flexible system operation. Each venturi processes 547,000 acfm which amounts to about one quarter of the maximum flue gas flow from the boilers. These scrubbers, which circulate process water treated with lime, provide final particulate removal while removing 50 percent of the flue gas SO_2. Overall particulate removal efficiency for the entire mechanical collector ESP scrubber system is 99 percent.

Before exiting the venturi scrubbers, the flue gas enters a spray-washed mist eliminator which removes entrained slurry from the flue gas. The gas leaves the scrubber, passes through a booster induced draft fan and then follows one of two pathways.

In the case of the three single-stage scrubber trains the gas enters a second demister which removes any remaining slurry entrained in the flue gas. The gas is then reheated and exhausted to the atmosphere through the stack.

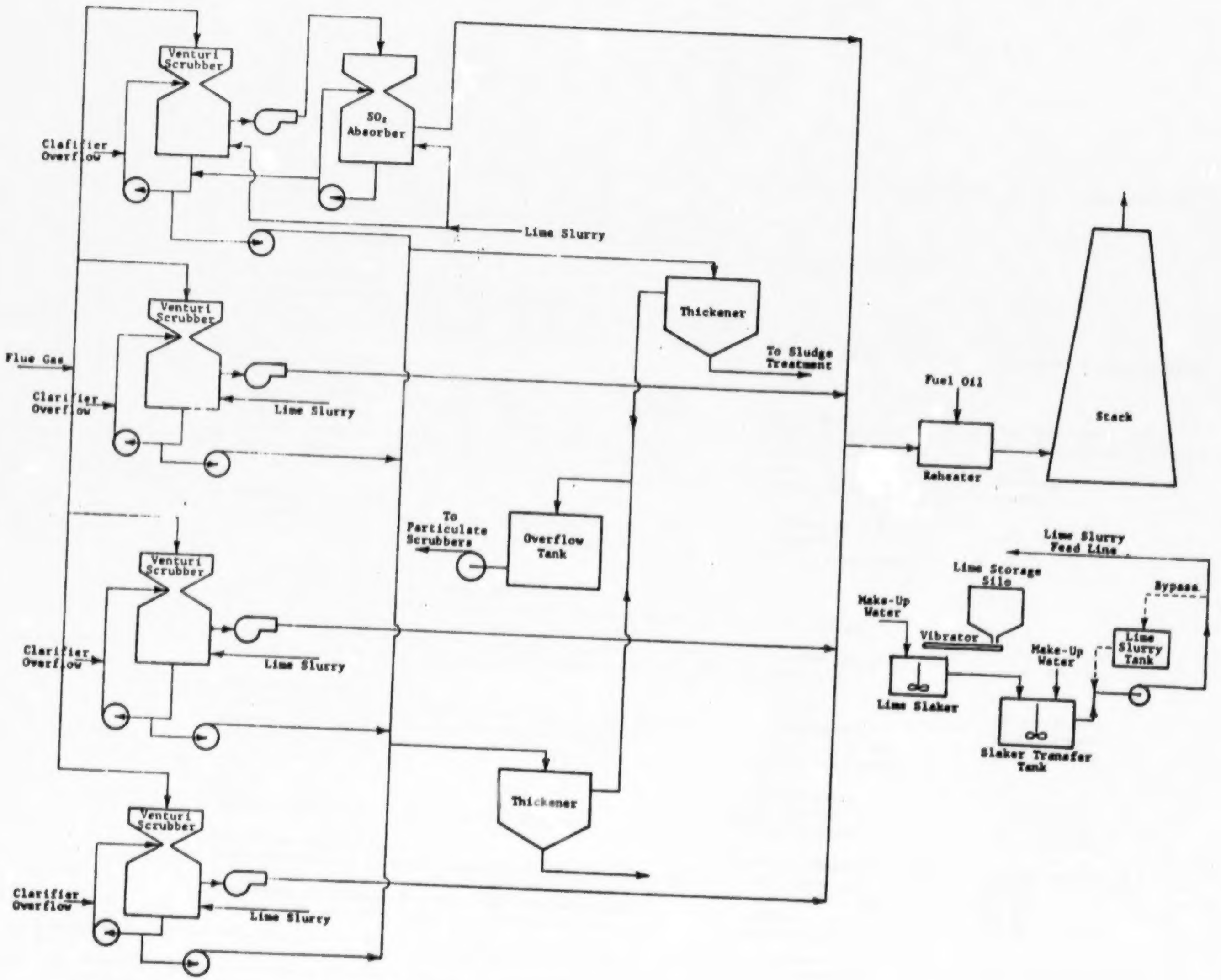

Venturi Scrubber
SO₂ Absorber
Clafifier Overflow
Lime Slurry
Venturi Scrubber
Flue Gas
Clarifier Overflow
Lime Slurry
Thickener
To Sludge Treatment
Fuel Oil
Reheater
Stack
To Particulate Scrubbers
Overflow Tank
Venturi Scrubber
Clarifier Overflow
Lime Slurry
Lime Slurry Feed Line
Lime Storage Silo
Bypass
Make-Up Water
Vibrator
Make-Up Water
Lime Slurry Tank
Lime Slaker
Slaker Transfer Tank
Thickener
Venturi Scrubber
Clarifier Overflow
Lime Slurry

Figure D-3. Phillips FGD System.

TABLE D-3. OPERATING CHARACTERISTICS OF THE PHILLIPS BOILER-SCRUBBER SYSTEM

Item	Description	Parameter	Value
1. Boiler	The Phillips Station consists of six dry-bottom, pulverized coal-fired boilers. The entire station has been retrofitted with an FGD system. The boilers were manufactured by Foster-Wheeler and installed during the period 1942 to 1956.	Power Rating Gross Net Without FGD Net With FGD Average Capacity Factor	 413 MW 397 MW 373 MW 66 Percent (1976)
2. Fuel	Medium-sulfur coal is burned in the boiler.	Sulfur Content Ash Content Heating Value	2.15 Percent 18.2 Percent 11,350 Btu/lb
3. Particulate Control	Particulates are controlled by Research-Cottrell Mechanical Collectors in series with electrostatic precipitators. The FGD system also removes particulates from the flue gas.	Removal Efficiency Mech. Coll. ESP FGD Systems TOTAL	 80.00 Percent 95.00 Percent 99.00 Percent
4. Absorbent Preparation	Lime is used to absorb the SO_2. Lime is fed from a storage silo at a controlled rate to a lime slaker where it is mixed with fresh makeup water. The slaked lime overflows to a slaker transfer tank where makeup water is added to provide a constant flow of lime slurry with a 15 percent solids concentraion.	Composition Calcium Oxide Other Stoichiometry	 95.0 Percent 5.0 Percent 1.3
5. SO_2 Control	Only one of the four scrubber trains is used exclusively for SO_2 control. The others remove about half of the SO_2 from processed flue gas.	Removal Efficiency Module 1 Module 2, 3 & 4	 90 Percent 50 Percent
6. FGD System	The FGD system consists of four modules of wet venturi-type scrubbers. Three of the trains are single-stage venturi scrubbers originally intended for particulate removal. The fourth train is a dual-stage venturi scrubber-absorber and is the prototype for determining the feasibility of two-stage scrubbing for compliance with SO_2 emission limits.	System Vendor Type Start-up Date Prescrubber Type Module Size	Chemico Retrofit 7/73 Variable-Throat Venturi 547,000 acfm @ 340°F
7. Demister	The demisters are an integral part of the Chemico venturi scrubbers. The gas flows down through the venturi and back up through the demisters. The demisters are chevron-type of fiberglass construction.	Demister Wash	Internal Automatic Spray
8. Fan	There is a booster fan downstream of each of the pre-scrubbers. The fans are equipped with fresh water sprays to remove any accumulation of solids from scrubber carryover.	System Pressure Drop	-

TABLE D-3. (Continued)

Item	Description	Parameter	Value
9. **Reheater**	A 316-C stainless steel section of the duct the stack is equipped with a direct oil-fired reheater unit that can raise stack gas temperatures as much as 30°F. Normal reheat is about 20°F.	Flue Gas Temperature Inlet Outlet	 110-120°F 140°F
10. Sludge Disposal	The waste sludge is stabilized by the addition of 200 pounds of calcilox per ton of dry solids in the sludge. The fixed sludge is transported to experimental plastic-lined ponds located about one mile from the station, where the material solidifies.	Pond/Landfill	-
11. Water Makeup	Both fresh water and recycle clarifier overflow are used in the system. The system operates	Fresh Water Makeup	635 gpm

In the case of the two-stage SO_2 absorber train, gas leaving the ID fan goes to a second absorber which is identical in size and mechanical design to the first stage venturi scrubber. The primary difference between the first and second stage scrubbers is that the second stage absorber is equipped with lime slurry injection nozzles. This results in removal of 90 percent of the SO_2 which compares to 50 percent for the single stage trains.

Desulfurization flue gas leaves the second stage scrubber through a spray washed demister. The gas is then reheated and exhausted to the atmosphere through the stack.

Lime for the FGD system is fed from a storage silo to a lime slaker where it is mixed with fresh water to form calcium hydroxide. The slaked lime then overflows to a transfer tank where makeup water is added until a 15 wt. percent solids slurry is produced.

Scrubbing liquor from the absorbers is withdrawn from a sump in the bottom of each absorber and circulated by two recycle pumps. Some of this recycle liquor is bled to the thickeners. Makeup liquor for the second stage is drawn from the slaked lime transfer tank while makeup water for the first stage scrubbers is bled from the second stage venturi recirculation loop.

The purge streams from the absorber and the four scrubbers enter a trough which feeds two 75 foot diameter thickeners. The overflow from these thickeners is pumped to a makeup return line which recirculates clarified liquor to the scrubber.

Undeflow from each thickener is pumped to one of three clay-lined sludge holding ponds. However, before the sludge enters the holding ponds, it is treated with a stabilizing agent. This promotes settling and curing of the sludge in the pond. Finally, the cured sludge is excavated from the pond and trucked to an off site disposal area.

D.4 LA CYGNE GENERATING STATION

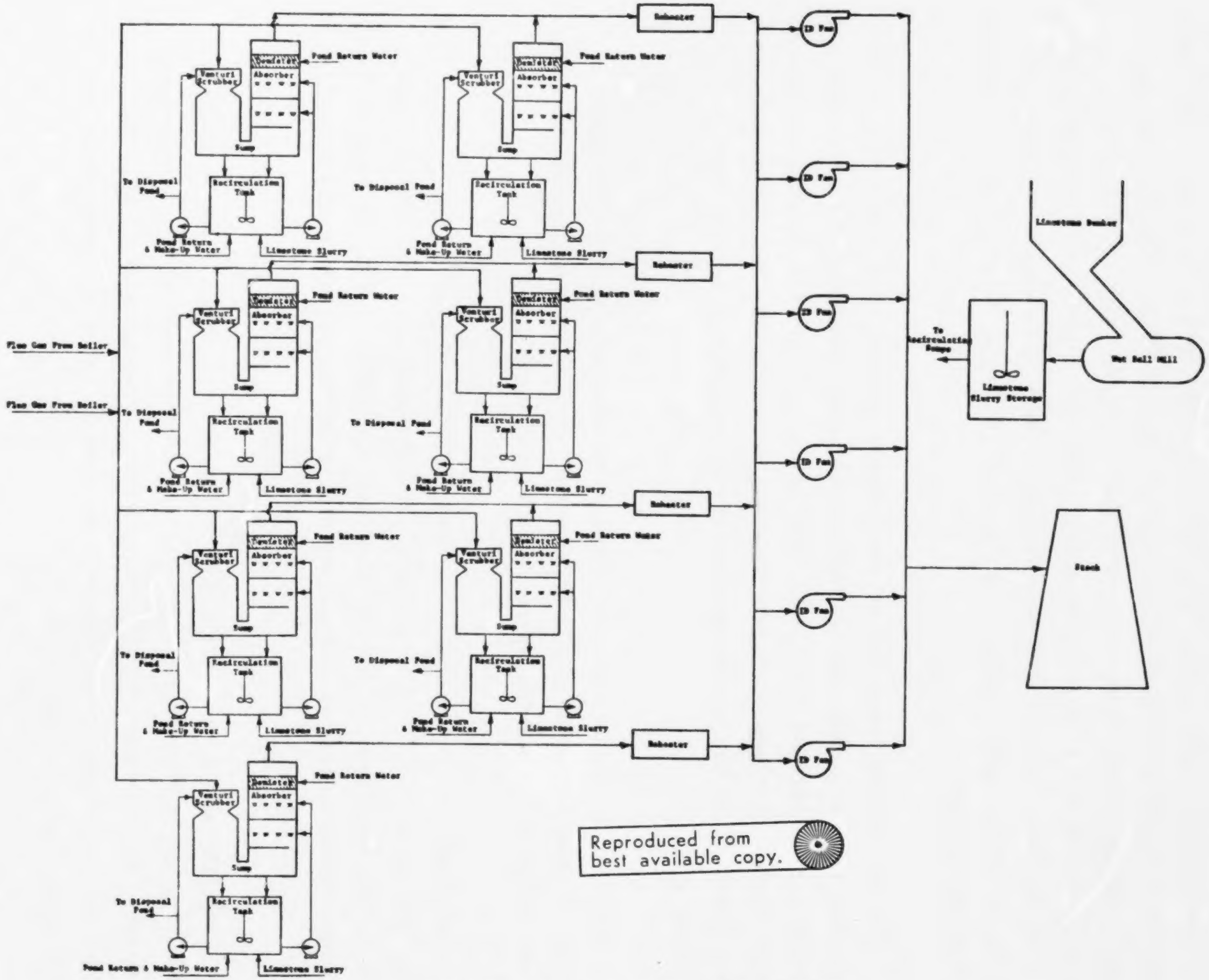
The LaCygne Power Generating Station of the Kansas City Power and Light Company is located about 55 miles south of Kansas City. This station has a single 874 MW, wet-bottom, coal-fired boiler fitted with an FGD system. The boiler was first fired in December, 1972 and placed in commercial service on June 1, 1973. The boiler is a base-load unit with an average capacity factor of 23 percent (1974). Both the boiler and the FGD system are Babcock and Wilcox design.

The FGD system installed at the LaCygne Station is a limestone slurry scrubbing process. The system consists of seven identical scrubber modules, limestone grinding and storage facilities, and a pond for disposal of unstabilized limestone sludge. Figure D-4 is a schematic for the FGD system and Table D-4 details the operating characteristics of the LaCygne boiler-scrubber system.

The LaCygne Station has no auxiliary particulate control equipment. The FGD system serves as the only means of particulate control and there is no provision to bypass the system when it is out of service.

Limestone for the scrubbing system is obtained from a nearby quarry and ground on site. A 60,000 ton supply is maintained near the coal storage area. This limestone is transported intermittently to two wet ball mills by the coal conveyor system. Limestone slurry leaves the mills and is stored in one of two slurry supply tanks.

Each FGD module is comprised of a venturi scrubber in series with a sieve tray absorption tower. The venturi removes most of the particulates from the entering flue gas while the absorber removes most of the SO_2 . Each module is capable of processing 394,300 acfm or about one seventh of the total flue gas flow from the boiler.



Flue Gas From Boiler
Flue Gas From Boiler
Venturi Scrubber
Demister
Absorber
Sump
Recirculation Tank
Pond Return Water
To Disposal Pond
Pond Return & Make-Up Water
Limestone Slurry
Reheater
ID Fan
Stack
Limestone Bunker
Wet Ball Mill
Limestone Slurry Storage
To Recirculation Sumps

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Figure D-4. La Cygne FGD System.

TABLE D-4. OPERATING CHARACTERISTICS OF THE LA CYGNE BOILER-SCRUBBER SYSTEM

Item	Description	Parameter	Value
1. Boiler	The LaCygne Power Generating Station has a single coal-fired boiler integrated with an FGD system. Both are of Babcock and Wilcox design and construction. The boiler is a wet-bottom cyclone-fired unit which began commercial operation on 6/1/73.	Power Rating	
		Gross	874 MW
		Net Without FGD	844 MW
		Net With FGD	820 MW
		Average Capacity Factor	23 Percent (1974)
2. Fuel	Low-grade, high-sulfur, sub-bituminous coal.	Sulfur Content	5.4 Percent
		Ash Content	24.4 Percent
		Heating Value	9420 Btu/lb
3. Particulate Control	The FGD system is the particulate control device for the La Cygne boiler. The venturi scrubber which precedes [illegible] the seven absorbers removes most of the particulates f[illegible] flue gas.	Removal Efficiency	97 to 99 Percent
4. Absorbent Preparation	Limestone slurry absorbs SO_2 from the flue gas. [illegible] limestone milling facilities consist of two wet ball mills rated at 108 ton/hr and two limestone holding tanks.	Composition	
		Silicates	5-7 Percent
		Calcium Carbonate	85-93 Percent
		Magnesium Carbonate	2.5 Percent
		Stoichiometry	1.7
5. SO_2 Control	The FGD system is used to control SO_2 emissions.	Removal Efficiency	70-83 Percent
6. FGD System	The FGD system consists of seven identical modules, each capable of processing approximately one-seventh of the maximum flue gas flow from the boiler. The FGD modules are comprised of a venturi prescrubber in series with a two-stage sieve tray absorber.	System Vendor	Babcock and Wilcox
		Type	New
		Start-up Date	6/1/73
		Prescrubber Type	Variable Throat Venturi
		Module Size	394,300 Acfm @ 285°F
7. Demister	A single stage Chevron type demister is located above a third sieve tray in each absorber. Two of the modules have a second demister. The demisters are washed continuously from below and intermittently from above. Demisters are constructed of fiberglass.	Demister Wash	
		Top	2100 gpm Pond Supernatent/ 1 min. every 8 hr.
		Bottom	130 gpm Pond Supernatent/ Continuous
8. Fan	There are 6 ID fans located between the reheaters and the stack. The suction side of these fans draws gas from a common header connecting all seven FGD modules.	System Pressure Drop	21-24 in. H_2O
9. Reheater	Flue gas exiting the absorber is reheated by heat exchange with steam coils. This is supplemented by injection of hot air into the flue gas stream.	Flue Gas Temperature	
		Inlet	121°F
		Outlet	175°F
10. Sludge Disposal	Limestone slurry is removed continously from the absorber recirculation tank and pumped directly to the sludge pond. This slurry is about 10 wt. percent solid and no treatment is used.	Pond/Landfill Requirements	400 Acre - Ft/yr
11. Make-up Water	La Cygne operates as a closed-loop system. Fresh water is added to make up for evaporative losses and water retained in the sludge.	Make-up Rate	---

Hot flue gas flows from the boiler and enters a venturi where it is contacted with limestone slurry which is injected through nozzles in the walls of the vessel. The gas and entrained slurry flow downward through the venturi throat where the particulates impinge on the slurry droplets.

After passing through the venturi, the flue gas enters a sump where a reduction in flue gas velocity causes entrained slurry droplets to fall from suspension. The gas then flows upward through the SO_2 absorption tower and passes through two perforated trays. The trays, which are wetted with limestone slurry sprays, provide an extended surface for absorption of SO_2 by the circulated slurry.

The scrubbed gas then passes through a third sieve tray which collects slurry carryover and reduces the load on the demister. Each absorption tower is fitted with a 10 inch high "Z" shape demister and two of the seven modules incorporate a second stage demister. As flue gas passes through the demister, fine mist droplets coalesce on the surface of the demister vanes and drip back into the tower. The demisters are washed by underspray and overspray manifolds. Supernatant from the sludge disposal pond is used for wash water. Each demister is washed continuously with 140 gpm of underspray while the overspray operates intermittently at 2100 gpm for 1 minute during each 8 hour period.

Flue gas exits the demisters and enters the reheater where the temperature is raised from 120°F to 175°F. Heat exchange with high pressure steam is the primary mechanism for reheat, however, this is supplemented by hot air injection on six modules.

Spent limestone slurry flows from the venturi/absorber sump to the recirculation tank. Fresh limestone feed is added to the recirculation tank and slurry is recycled to the absorbers. In addition, a purge stream of 10 wt. percent solids is continuously withdrawn from the recirculation tank and pumped directly to the sludge pond. Pond overflow water is recycled to the FGD system, thus providing closed loop operation.

D.5 GREEN RIVER GENERATING STATION

The Green River Power Generating Station of the Kentucky Utilities Company is located on the Green River near Central City, Kentucky. The station which is operated as a peak load unit, consists of four boilers, two generating units and an FGD system. The FGD system has been retrofitted on boilers 1, 2 and 3 which have a combined generating capacity of 64 MW.

The Green River FGD system is a lime slurry scrubbing process. The system was designed by American Air Filter Company and it began operation in September, 1975. This FGD system consists of one scrubber, lime storage and slaking facilities, and a sludge disposal pond. Figure D-5 is a schematic of the FGD system and Table D-5 details the operating characteristics of the Green River boiler-scrubber system.

As illustrated in Figure D-5, flue gas flows from the boilers through a forced draft fan and then enters the scrubber module. The module is designed to process 360,000 acfm of flue gas. It consists of a venturi prescrubber in series with a mobile bed absorber.

The prescrubber removes most of the particulates and some SO_2 from the gas stream. After passing through the prescrubber, flue gas enters the bottom of the absorber and flows upward through the mobile bed contactor. This mobile bed consists of ten sections with overhead lime slurry sprays. As flue gas passes through the mobile bed, SO_2 is absorbed by the recirculating slurry and subsequently reacts with lime to form calcium sulfite.

Spent slurry exits the scrubber and goes to a reactant tank which is divided into three sections. The slurry enters the return section (Figure D-5) where makeup water and fresh lime slurry are added. The second and third sections of the reactant tank provide sufficient retention time for

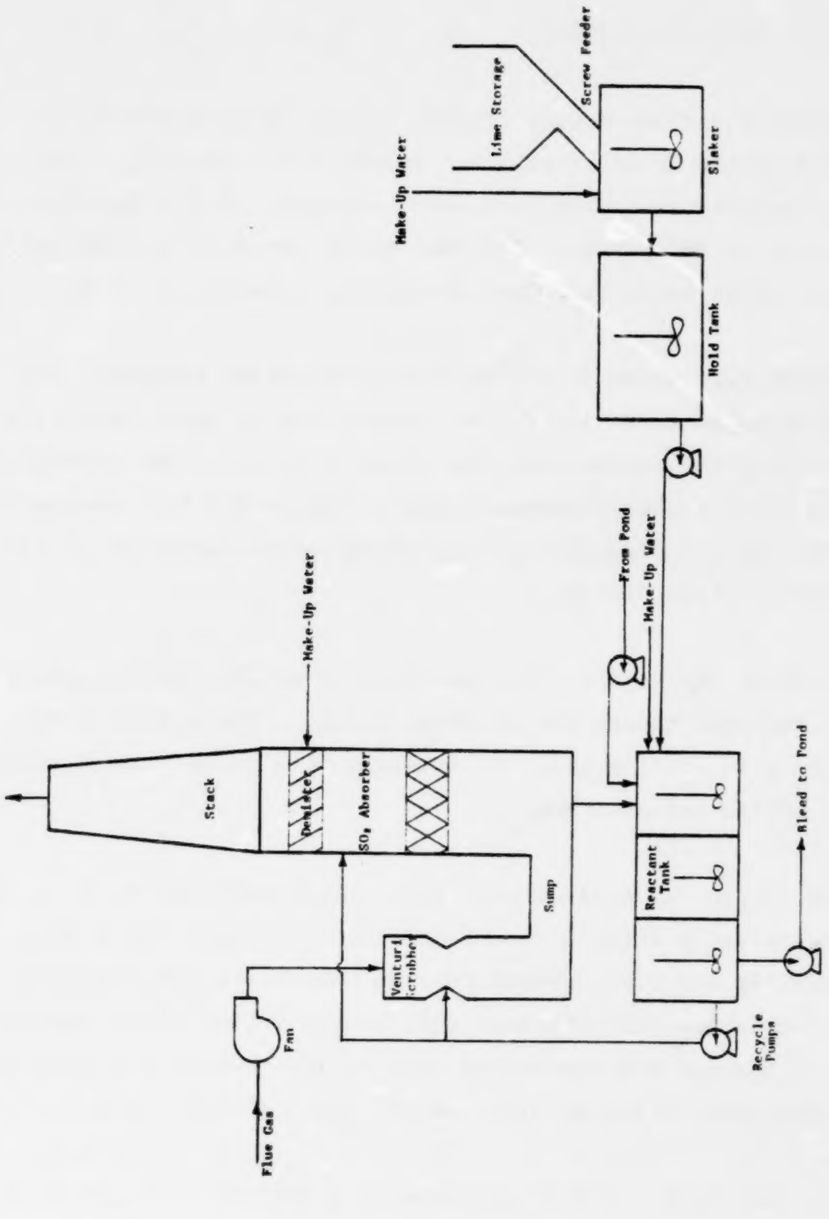
Flue Gas
Fan
Venturi Scrubber
Sump
Stack
Demister
SO_2 Absorber
Make-Up Water
Recycle Pumps
Reactant Tank
Bleed to Pond
From Pond
Make-Up Water
Hold Tank
Slaker
Lime Storage
Screw Feeder
Make-Up Water

Figure D-5. Green River FGD System.

TABLE D-5. OPERATING CHARACTERISTICS OF THE GREEN RIVER BOILER-SCRUBBER SYSTEM

Item	Description	Parameter	Value
1. Boiler	The Green River Station has four coal-fired boilers, three of which have been retrofitted with an FGD system. Green River is a peak load station which normally operates five days a week.	Power Rating	
		Net with FGD	64
		Average Capacity Factor	
2. Fuel	A high-sulfur, western Kentucky coal is burned in the boilers.	Sulfur Content	3.8 Percent
		Ash Content	-
		Heating Value	-
3. Particulate Control	The FGD system is used in conjunction with mechanical collectors.	Removal Efficiency	
		Mechanical Collectors	-
		FGD System	99.7 Percent
4. Absorbent/Preparation	Lime slurry is used to absorb SO_2 from the flue gas. Pebble lime is purchased and stored in a 500-ton capacity bin. Lime is slaked in an agitated tank to produce a 20 percent solids slurry.	Composition	-
		Stoichiometry	-
5. SO_2 Control	The FGD system controls SO_2 emissions in order to meet air quality regulations.	Removal Efficiency	80 Percent
6. FGD System	The FGD system consists of a single module capable of treating all of the flue gas from boilers 1, 2, and 3. The module consists of a venturi prescrubber in series with a mobile-bed absorber.	System Vendor	American Air Filter Co.
		Type	Retrofit
		Start-Up Date	9/75
		Prescrubber Type	Venturi
		Module Size	360,000 acfm @ 300°F
7. Demister	A cyclone demister is used to remove entrained mist from the flue gas stream leaving the absorber.	Demister Wash Top	-
8. Fan	A forced draft booster fan is located upstream of the venturi prescrubber.	System Pressure Drop	-
9. Reheater	There is no reheater on this system.	-	-
10. Sludge Disposal	Sludge is pumped to an unlined pond. Clear pond overflow is returned from the pond to the reactant tank.	Pond Landfill Requirements	-
11. Water Makeup	Makeup water is added to the system to replace evaporative losses and water which is retained in the sludge.	Makeup Rate	-

completion of the sulfite/sulfate precipitation reactions. Slurry from the third section of the reaction tank is recycled to the venturi prescrubber and the absorber.

Fresh slurry is prepared by feeding pebble lime into an agitated slaking tank. Slurry is discharged from the slaker hold tank and then pumped to the reactant tank.

A bleed stream is withdrawn from the reactant tank to remove sulfite/sulfate solids and collected fly ash. This bleed is pumped to the disposal pond where the solids settle. Pond overflow is recycled to the FGD system thus providing closed loop operation.

D.6 PADDY'S RUN GENERATING STATION

The Paddy's Run Power Generating Station of the Louisville Gas and Electric Company is located on the Ohio River in Rubbertown, Kentucky. Unit No. 6 at the Paddy's Run Station has been retrofitted with an FGD system. This unit is a 70 MW, dry-bottom, pulverized-coal-fired boiler designed and installed by Foster-Wheeler in 1951. It is used only during periods of peak load and the average capacity factor is approximately 5 percent.

The FGD system, which uses a lime slurry to absorb SO_2, was designed and manufactured by Combustion Engineering, Inc. and placed in service in April, 1973. The system consists of two identical absorbers, lime slurrying facilities, and sludge dewatering equipment. The system operates closed-loop with respect to process water. Fresh water is used to replace evaporative losses and water retained in the sludge. Figure D-6 is a schematic of the Paddy's Run FGD system and Table D-6 illustrates the operating characteristics of the boiler-scrubber system.

Flue gas from Unit No. 6 flows through a Research-Cottrell electrostatic precipitator prior to entering the FGD system. The ESP operates with an

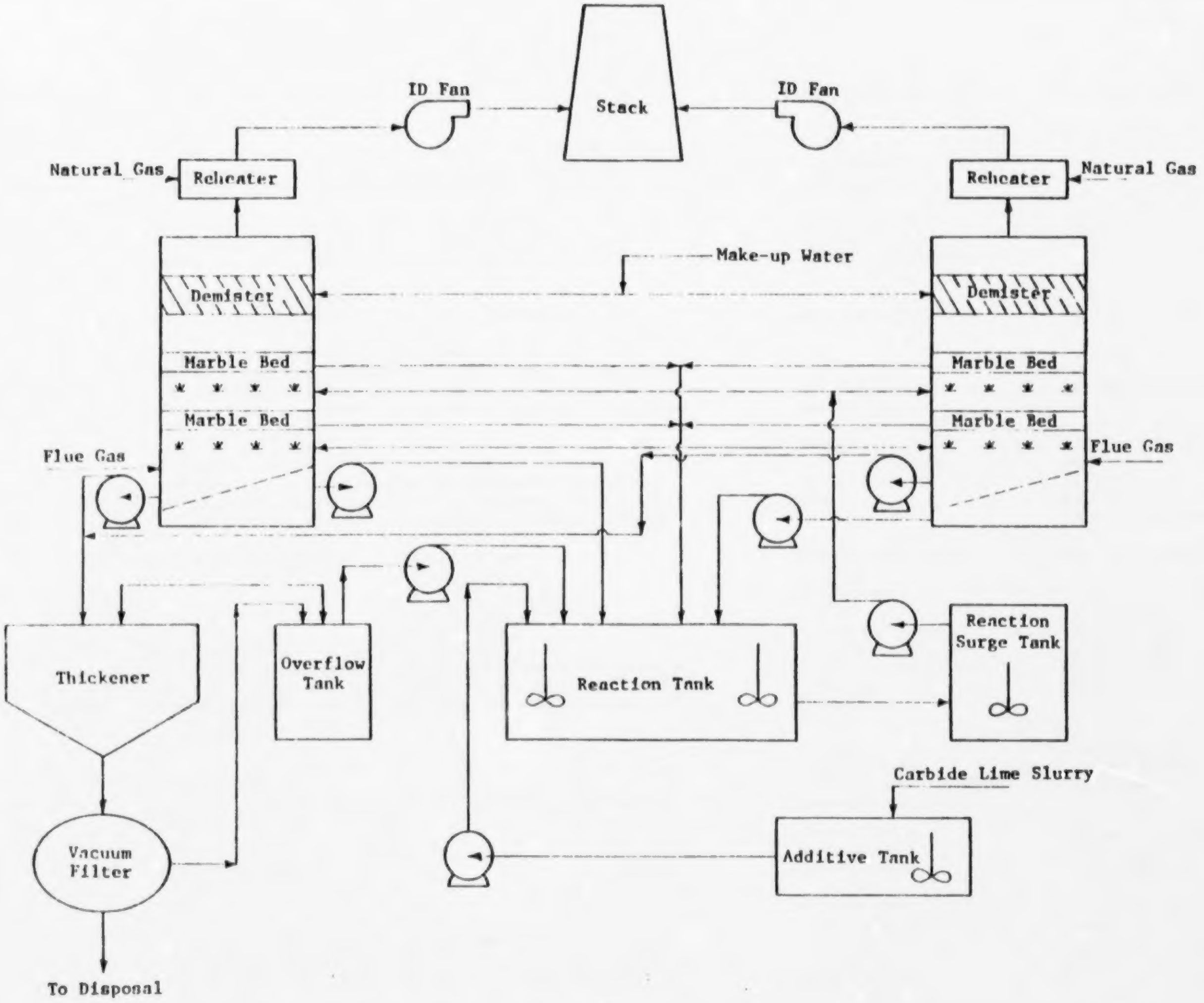
ID Fan
Stack
ID Fan
Natural Gas
Reheater
Reheater
Natural Gas
Make-up Water
Demister
Demister
Marble Bed
Marble Bed
Marble Bed
Marble Bed
Flue Gas
Flue Gas
Thickener
Overflow Tank
Reaction Tank
Reaction Surge Tank
Carbide Lime Slurry
Additive Tank
Vacuum Filter
To Disposal

Figure D-6. Paddy's Run FGD System.

TABLE D-6. OPERATING CHARACTERISTICS OF THE PADDY'S RUN BOILER-SCRUBBER SYSTEM

Item	Description	Parameter	Value
1. Boiler	Unit No. 6 of the Paddy's Run Power Generating Station is a dry-bottom, pulverized-coal-fired boiler. The boiler was manufactured by Foster Wheeler and installed in 1951.	Power Rating	
		Gross	70 MW
		Net Without FGD	65 MW
		Net With FGD	63 MW
		Average Capacity Factor	5. Percent (1974)
2. Fuel	High sulfur coal.	Sulfur Content	3.71 Percent
		Ash Content	13.8 Percent
		Heating Value	12,400 Btu/lb.
3. Particulate Control	A Research-Cottrell ESP provides primary particulate control for Unit No. 6	Removal Efficiency	
		Electrostatic Precip.	99.1 Percent
		FGD Systems	85.90 Percent
		TOTAL	99.9 Percent
4. Absorbent/Absorbent Preparation	A carbide lime slurry is used to absorb SO_2 from the flue gas. This lime is purchased as a sludge by-product from an actylene manufacturing plant. The lime sludge is mixed with water in an agitated slurry tank.	Composition	
		Silica	1.5 Percent
		Calcium Hydroxide	92.5 Percent
		Calcium Carbonate	1.9 Percent
		Magnesium Oxide	0.1 Percent
		Other	4.0 Percent
		Stoichiometry	1.0
5. SO_2 Control	The FGD system is used to control SO_2 emissions.	Removal Efficiency	85 - 90 Percent
6. FGD System	The FGD system consists of two identical modules each designed to process 50 percent of the maximum flue gas flow from Unit No. 6. The modules are two-stage, marble bed absorbers.	System Vendor	Combustion Engineering
		Type	Retrofit
		Start-up Date	4/73
		Prescrubber Type	None
		Module Size	175,000 ACFM @ 350°F
7. Demister	A two-stage, chevron-type demister is located 4 feet above the upper marble bed in each absorber. The demisters are washed intermittently from above and below by fresh make-up water. Demisters are of fiberglass construction.	Demister Wash	
		Top & Bottom	200 gpm/10 min. every 8 hr.
8. Fan	There is an induced draft fan which is located at the reheater outlet on each module.	System Pressure Drop	15 - 16 in. H_2O
9. Reheater	Reheat for the flue gas is provided by mixing the desulfurized gas with hot combustion gases. Natural gas is fired in burners located in the duct above the demister.	Flue Gas Temperature	
		Inlet	126°F
		Outlet	165°F
10. Sludge Disposal	Sludge is first thickened in a clarifier. Flocculent is added at this point. Clarifier underflow is processed by a rotary vacuum filter to a 40% solids sludge. This sludge is trucked off-site to an unlined pond.	Pond/Landfill Requirements	---
11. Water Make-up	The system is a closed water loop operation. The supernatant from the clarifier and the filtrate from the filter are recycled to the system. Fresh water is added to replace evaporative losses and water retained in the sludge.	Fresh Water Make-up	135 gpm

efficiency of 99.1 percent and provides primary control of particulate emissions from the boiler.

Flue gas flows into the FGD system and is split between the two modules, each capable of processing 175,000 acfm. Flue gas enters the scrubber module near the base where it contacts sprays which provide a constant supply of slurry to the underside of the marble beds. This slurry also serves to cool the flue gas adiabatically to its saturation temperature before it enters the marble bed. The wetted flue gas rises through the bed and carries the slurry with it. The vigorous action of the marbles mixes the flue gas and slurry to form a "turbulent layer" above the marble bed. The turbulent layer provides the necessary surface area to effect the required degree of SO_2 absorption and particulate removal. After emerging from the second marble bed, the clean flue gas passes through a two-stage chevron mist eliminator where entrained water droplets are agglomerated and removed. The flue gas then passes through a gas-fired reheater, through a booster fan, and out the stack.

Spent slurry is withdrawn continuously from the absorbers and sent to a reaction tank where fresh lime is added and calcium sulfite/sulfate precipitate. Slurry from the reaction tank is returned to the absorber while a stream is bled to a thickener where the sulfite/sulfate solids are concentrated.

The underflow from the thickener is sent to a rotary vacuum filter. Filter cake is trucked to an off-site landfill area. Vacuum filtrate is recycled to the thickener, and pumped back to the reaction tank to close the liquid effluent loop.

Lime for the scrubber is obtained as sludge which is known as "carbide lime". It is generated as a waste by-product from a nearby acetylene manufacturing operation.

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